Geophysical Research Abstracts, Vol. 9, 09699, 2007
SRef-ID: 1607-7962/gra/EGU2007-A-09699

Non-Stationary Functional Series TARMA Modeling of Strong Ground Motion: The Case of Kythira Island Mw 6.9 Earthquake in Greece

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The modeling, analysis based on the determined model, and simulation of ground motion due to an earthquake may significantly enhance and direct the study of structural behavior under seismic excitation. The main difficulty in modeling such signals stems from their strongly non-stationary – in terms of both variance and frequency content – nature. The available modeling methods may be broadly classified as either *time* or *frequency* domain, [1].

This paper considers the modeling and simulation of strong ground motion recorded from the Seismological Network of Crete, for the case of Kythira island earthquake in Greece (occurred on 8-Jun-2006, N 36.31, E 23.25, M_w 6.9, depth 60 km), via a time-domain method which utilizes Functional Series (FS) Time-dependent AutoRegressive (AR) Moving Average (MA) ARMA (TARMA) models. TARMA models constitute extensions of their stationary ARMA counterparts in that their parameters are explicit functions of time, belonging to functional spaces spanned by sets of preselected deterministic functions of time. A TARMA(n_a, n_c) model, with n_a, n_c designating its autoregressive (AR) and moving average (MA) orders, respectively, is thus of the form:

$$x[t] + \underbrace{\sum_{i=1}^{n_a} a_i[t] \cdot x[t-i]}_{\text{AR part}} = e[t] + \underbrace{\sum_{i=1}^{n_c} c_i[t] \cdot e[t-i]}_{\text{MA part}} \qquad e[t] \sim \mathrm{NID}\left(0, \sigma_e^2[t]\right)$$

with t designating discrete time, $x[t]$ the non-stationary signal to be modelled, $e[t]$ an (unobservable) uncorrelated (white) *innovations* sequence with zero mean and

time-dependent variance $\sigma_e^2[t]$ that "generates" $x[t]$, and $a_i[t], c_i[t]$ the model's time-dependent AR and MA parameters, respectively, projected on preselected deterministic time functions (basis functions). NID$(\cdot,\cdot)$ stands for normally independently distributed with the indicated mean and variance. This TARMA form may often be defined within a specific time interval, say $[t_0,\ t_f]$.

The representation of non-stationary signals and/or systems through TARMA models offers a number of potential advantages, such as: (i) representation parsimony; (ii) improved accuracy, resolution and tracking of time-varying dynamics; and, (iii) flexibility in analysis, simulation, prediction, fault diagnosis and control, over other non-parametric and parametric techniques [2], reveal the properties and the characteristics of the generation mechanism, and has been proved particularly effective for both the modeling and simulation of strong earthquake ground motion, [1].

The *aim* of this study is twofold:

(a) The development of a systematic and automated method for TARMA model estimation, and

(b) Its application to a number of recorded signals during the aforementioned earthquake.

The proposed estimation method, is comprised of an orthogonal parameter estimation algorithm [3, 4], and the Two-Stage Least-Squares Method (2SLS), [2]. It is based on exclusively linear techniques, thus minimizing the computational load. Nevertheless, its main advantage is that the tedious model structure selection problem (subspace dimensionalities, specific basis functions, etc.), often tackled via time consuming trial-and-error or integer optimization schemes (such as genetic and/or evolutionary algorithms, [2]), is in the present context overcome due to the use of orthogonal parameter estimation which "automatically" selects the most important model terms, while it provides parameter estimation at the same time.

The proposed methodology was applied to seismograms recorded from various stations of the Seismological Network of Crete, and the results are characterized by high accuracy in terms of both modeling (representation capability) and simulation (signal synthesis). The estimated models, are proven to accurately capture the underlying mechanism characteristics (eigenfrequencies, damping ratios).

This work was supported from the project "Archimedes II: Support of Research Teams of Technological Educational Institute of Crete", sub-project No 2.2.4 entitled: "Combined Technological & Methodological Approach of Geoelectromagnetic Study of Western Crete” in the frame of Operational Programme for Education and Initial Vocational Training (O.P. “Education”) co-financed from European Social Fund of European Union and national resources of Greece.

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