Computers and Structures 147 (2015) 26–35

Contents lists available at ScienceDirect

Computers and Structures

journal homepage: www.elsevier.com/locate/compstruc

Spectrum-compatible accelerograms with harmonic wavelets

Domenico Cecini, Alessandro Palmeri *

School of Civil and Building Engineering, Loughborough University, Sir Frank Gibb Building, Loughborough LE11 3TU, England, United Kingdom

ARTICLE INFO

Article history:
Accepted 9 October 2014
Available online 31 October 2014

Keywords:
Artificial accelerograms
Earthquake engineering
Harmonic wavelet transform (HWT)
Signal processing
Spectrum-compatible accelerograms

ABSTRACT

Modern building codes allow the analysis and design of earthquake-resistant structures with recorded and/or generated accelerograms, provided that they are compatible with the elastic design spectrum. The problem then arises to generate spectrum-compliant accelerograms with realistic non-stationary characteristics, which in turn may play an important role in the non-linear seismic response. In this paper, an iterative procedure based on the harmonic wavelet transform is proposed to match the target spectrum through deterministic corrections to a recorded accelerogram, localised both in time and frequency. Numerical examples demonstrate the performance of this approach, which can be effectively used in the design practice.

1. Introduction

Building codes conventionally define the seismic action through the elastic design spectrum (EDS), which is a way to represent synthetically the seismic hazard at a given site. Furthermore, the response spectrum analysis is widely recognised as the reference method for designing ordinary earthquake-resistant structures. In order to achieve a better understanding of the structural and non-structural performance under seismic forces, however, the time-history analysis is preferable. This method of analysis is particularly useful for non-conventional buildings, e.g. when the inelastic behaviour of some structural components (including isolators and dampers) must be accurately modelled, and cannot be simply accounted for by modifying the ordinates of the design spectrum with the ductility-dependent behaviour factor.

One of the key issues while carrying out the time-history analysis is the appropriate selection of the seismic input (e.g. Ref. [1]). International codes allow using both natural (i.e. recorded) and artificial (i.e. generated) time histories of ground acceleration and, besides generic prescriptions of being representative of the site hazard from a seismological point of view, their on-average spectrum-compatibility is required. That is, if the elastic response spectrum (ERS) is computed for each accelerogram of the selected suite, the mean value of the spectral ordinates for the periods of vibration within the rage of interest must satisfy the compatibility conditions with the corresponding ordinates of the EDS. As a consequence, if this suite is used to run linear-elastic time-history analyses, the discrepancy between the average seismic response so obtained and the EDS prescribed by the code will be small enough to be acceptable for design purposes.

In this context, the direct use of natural accelerograms is an attractive option and nowadays, with few exceptions of very soft soils in areas of high seismicity, numerous records are available. Unfortunately, the need to generate artificial ground motions still arises from the difficulty to form groups of motions with reasonable scatter around the target spectrum. These artificial records can be either simulated signals or recorded accelerograms modified to cope with the code prescriptions. Matching the EDS, however, is not a trivial task, mainly because the EDS given by seismic codes is a conventional and indirect representation of the expected ground shaking at a given site under some conventional design scenarios (i.e. for given return period and soil conditions), while an accelerogram provides a direct and full representation of the seismic action for a single event.

Importantly, the mapping between ERS and accelerograms is not bijective, as accelerograms provide richer information. Indeed, intensity, frequency content and duration of the ground shaking jointly contribute to build the ERS, but it is not possible to find them back individually. As a matter of fact, while a unique ERS can be computed from an accelerogram, a number of diverse accelerograms can be associated to (i.e. are compatible with) a target EDS. It follows that some of the above quantities must be specified to obtain the sought spectrum-compatible accelerograms (e.g. overall duration and energy content). In other words, the richer information allowed by the direct use of accelerograms (which is what makes worthwhile a time-history analysis for non-linear

* Corresponding author.
E-mail addresses: A.Palmeri@lboro.ac.uk, Dynamics.Structures@gmail.com (A. Palmeri).

http://dx.doi.org/10.1016/j.compstruc.2014.10.013
0045-7949/

structures, even if computationally more demanding) must be provided apart from the EDS offered by the seismic code.

Two alternative strategies can be pursued in this respect, as the additional information required to customise the generated accelerograms may be based either on the use of prediction laws (e.g. [2,3]), derived from seismological and geotechnical data, or on recorded ground motions (e.g. [4–9]). In both cases, the compatibility with the EDS is achieved while retaining some direct or indirect information on the expected non-stationary features in terms of amplitude and frequency content of the seismic action.

As far as the simulation of accelerograms is concerned, a number of different methods are available in the literature (for a review, see Refs. [10–12]), the vast majority of them being stochastic, i.e. they gain a certain level of abstraction from the underlying physical phenomenon. That is, the actual seismic genesis is not considered, and ground motion signals are mathematically handled as samples of a stationary or non-stationary random process [13–15,2,3,9]. Nonetheless, accelerograms generated in this way may not be ideal for some applications, especially for geotechnical systems (e.g. the Italian building code published in 2008 [16] explicitly bans their use for such applications) and for analyses where the energy content plays a crucial role [17,18].

In this framework, signal processing comes helpful to analyse, generate and manipulate accelerograms to be employed for different applications of earthquake engineering. A common practice is to use the Fourier transform (FT) to look at the recorded/generated signals in the frequency domain, where the distribution of the seismic energy at different frequencies becomes apparent. On the other hand, many studies (e.g. [19,20]) have shown the importance of modelling the temporal non-stationarity in the frequency content of the ground motion to properly assess the response of softening non-linear structures, and in this respect the accelerograms' non-stationary characteristics can be easily analysed in the time domain.

As a matter of fact, time and frequency domains are in a kind of dualism because they are capable of highlighting some relevant features of the signal, while hiding some others. Joint time–frequency signal representations can be therefore deemed as a powerful strategy to analyse the evolutionary frequency content of accelerograms, and getting the best from the two domains. Among them, the wavelet analysis (e.g. [21,22]) is a very promising tool, as it exploits localised functions (wavelets) instead of ever-lasting harmonics as a base to decompose a signal. The harmonic wavelet transform (HWT) enjoys the additional advantage of overcoming the limitations of the classical FT without losing a meaningful engineering interpretation in terms frequency content.

Further extending some preliminary results presented in [23], a novel HWT-based approach is proposed to generate a set of spectrum-compatible accelerograms, which allow satisfying the compatibility conditions with a target EDS starting from a parent accelerogram, while retaining the bulk of its non-stationary characteristics in terms of amplitude and frequency. This paper specifically addresses the problem of modifying deterministically a parent accelerogram in order to satisfy the compatibility requirements, while a second paper will be devoted in the future to the stochastic generation of an arbitrary number of time histories embedding the desired joint time–frequency properties of the spectrum-compatible signal, and to elucidate the optimal compromise between the two domains. The potential of the HWT in these two applications (deterministic correction and stochastic generation) has been partially shown in Ref. [23], and an additional effort has been done now in order to improve the required algorithms, facilitate the implementation and quantify their performance, also in comparison with previous research of other investigators.

This paper focuses on the problem of the deterministic correction and the main novelty lies in the fact that (to the best of the authors' knowledge) for the first time in the literature two complementary earthquake spectra (in terms of peak pseudo-acceleration, S_{PA}, and time instant at which such peak is attained, S_{ToM}) are jointly considered to calculate the corrective term in each iteration (allowing a simultaneous localisation of the deterministic corrections in both time and frequency domains). Indeed, although other applications of harmonic and non-harmonic wavelets can be found in the technical literature, the performance of existing methods are not completely satisfactory, as they do not take full advantage of their joint time–frequency localisation capabilities. In the method proposed by Mukherjee and Gupta [4], for instance, the Littlewood-Paley (L-P) basis of orthogonal wavelets (e.g. [24]) is used to decompose a recorded accelerogram into a finite number N of sub-signals with non-overlapping frequency bands, and then each sub-signals is iteratively scaled to match the target EDS. In their procedure, however, the sub-signals are uniformly scaled for the whole duration of the recorded accelerogram (i.e., the localisation is not exploited in the time domain), and therefore more energy is added than is strictly necessary. A similar matching scheme has been recently adopted by Giaralis and Spanos [15] as a way of post-processing the non-stationary samples generated from an analytically-defined uniformly-modulated (i.e. quasi-stationary) evolutionary power spectral density (PSD) function. Suárez and Montejo [5] have carried out the iterative spectral matching of a recorded accelerogram with a new family of wavelets, based on the impulse response function of an underdamped single-degree-of-freedom (SDoF) linear oscillator. Although the compatibility with the EDS is achieved, in all the results presented in their paper the amplitude of the corrective term is of the same order as the peak ground acceleration of the recorded signal (if not significantly higher), and such heavy adjustments reduces the practical advantages of their procedure in comparison with a direct stochastic generation. Aimed at overcoming such shortcomings, the proposed HWT-based matching scheme fully exploits the wavelets' localisation capabilities in both time and frequency domain, and in this way reduces the additional energy required to reach the spectral compatibility.

2. Harmonic wavelet analysis

The wavelet analysis consists of projecting a given signal on a convenient set of functions, called wavelets, which can be generated by scaling and shifting a mother wavelet [21]. In the continuous wavelet transform, the coefficient $a_{u,s}$ at scale s and position u of the signal $f(t)$ is given by:

$$a_{u,s} = \int_{-\infty}^{+\infty} f(t)\,\overline{\psi_{u,s}}(t)\,\mathrm{d}t, \tag{1}$$

where the over-bar denotes the complex conjugate, while:

$$\psi_{u,s}(t) = \frac{1}{\sqrt{s}}\,\psi\left(\frac{t-u}{s}\right) \tag{2}$$

is the mother wavelet $\psi(t)$ scaled by the parameter $s \in \mathbb{R}^+$ (controlling the frequency distribution) and shifted by the parameter $u \in \mathbb{R}$ (localising the function at around the time instant $t = u$). The inverse continuous wavelet transform is given by:

$$f(t) = \frac{1}{C}\int_{-\infty}^{+\infty}\int_{0}^{+\infty} \frac{1}{s^2}\,a_{u,s}\,\psi_{u,s}(t)\,\mathrm{d}s\,\mathrm{d}u, \tag{3}$$

in which C is simply a normalisation constant.

Unlike a harmonic wave, which is an ever-lasting periodic function, a wavelet is a decaying function, and this feature enables the localisation in time domain. Families of wavelets can be conveniently generated in a way to form an orthogonal basis, so that the wavelet transform is bijective, giving a unique representation