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An optimization method for the generation of ground motions compatible with multi-damping design spectra

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ABSTRACT

For some crucial engineering projects, a compatible time history of ground motions is required as a loading input for seismic dynamic analysis. The compatibility with multi-damping design spectra is critical to make sure the high reliability of analysis results. In previous methods, ground motions were hard to be tuned highly compatible with multi-damping design spectra.

Hence we propose a method to optimize the compatibility of a seed ground motion history, which is either obtained from actual seismic records or generated from previous methods, by superimposing adjusted ground motions in the time domain through the L_∞ norm minimization. The optimization process makes the influences of the superimposed ground motions to the response spectra be under control by constraining objective variables. The high precision of the method is demonstrated by a concrete example, in which the max difference between the response spectra of the optimized ground motions and the design spectra for RG1.60 data [1] is 5.06% under five different damping ratios, and all response spectra envelope the design spectra.

1. Introduction

Seismic response history analysis (SRHA) is an approach to perform non-linear dynamic analysis for critical structures, such as dams and nuclear power plants [2,3]. In the procedure of SRHA, representative time histories are needed to perform the analysis, which may come from actual strong ground motion records or may be artificially generated.

The response spectrum of ground motions is defined as a plot of the peak value of a response quantity. The quantity, which may be a displacement, a velocity, or an acceleration, is a function of natural vibration period T and damping ratio ζ of a linear single degree-of-freedom (SDOF) system. In this paper, the quantity is taken as the acceleration, and the terminologies *time history* and *ground motions* are interchangeable to represent the acceleration records, which are used as an input for structural analysis.

Seismic hazard is represented by the predicted ground motion intensity with rates of exceedance. For dynamic aseismic analysis of structures, ground motion with prescribed intensity levels is required and critical for the reliability of the analyzed results. The intensity levels could be peak ground acceleration (PGA) or spectral accelerations for a variety of periods, in which the latter consists of a target spectrum or called a design spectrum. For example, the conventional design spectra [1] and the Uniform Hazard Spectra (UHS) [4,5] are widely used. Compatibility with design spectra is a critical factor for the representability of time histories, and this has been prescribed in seismic design codes [1,6].

There are two main reasons to use spectrum compatible time histories. (1) The analysis result from spectrum compatible time histories has lower dispersion [7]. (2) Lots of regions in the world do not have sufficient ground motion records [8].

The structures, systems, and components of a nuclear power plant have different damping ratios. Thus it has been expected that the multi-damping response spectra of input ground motions should match the target design spectra well for performing the time history analysis. It is relatively easy to generate a spectrum compatible time history under a single damping ratio. However, under the requirements of multi-damping ratios, the max difference between response spectra and design spectra is hard to control [9].

The generation of ground motions compatible with design spectra has been an active research area over the past three decades. Earlier research works were reviewed by [10]. From the stochastic view of the time history, some works [11] represent the time history in the form of superimposed Fourier series, in which

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the Fourier amplitude and phase are adjusted iteratively to match the design spectra. To characterize the non-stationary behavior of the amplitude, various envelope functions are proposed [12–16].

Furthermore, it has been widely recognized that the frequency content in strong ground motion records is also non-stationary. In the work of [17,18], an adjustment framework has been proposed based on solving linear equations regarding to the weights of basis functions for the adjustment. Under this framework, evolutionary power spectra have been used to characterize the non-stationarity of frequency [19–21], and new kinds of wavelets are proposed which have better properties on stability and drift corrections on velocities and displacements [22–24]. Moreover, the directionality of ground motions is considered in the work of [25]. Besides wavelets for the adjustment, wavelet transform [26,27] is another sharp tool to make the time history be represented in the form of time-dependent frequency components. Recently, Hilbert–Huang transform is applied to retain the instantaneous frequency characteristics of ground motion records [28,29].

Besides the research to make the simulated ground motions approximate the characteristics of real records, another effort branch in this direction is to enhance the match precision between the response spectra and the design spectra. For many approaches of representing time histories in the form of Fourier series [11], wavelet bases [24], or decomposed with Empirical Mode Decomposition (EMD) [29], by adjusting the coefficients in these representations is hard to achieve a high match precision, especially for multi-damping design spectra. Therefore, after the selection and adjustment of coefficients, an iterative process to adjust the ground motions in the time domain is needed to improve the precision.

For many approaches of adding ground motions in the time domain [11,22,30–32,9], the added motions are dedicated to the current maximal spectral difference from the design spectra. Thus in each step the added ground motions will fix one peak response under the corresponding frequency and damping ratio. However, the added ground motions will influence other responses for other frequencies and damping ratios. Refs. [17,18] extended the method of [11] through solving linear equations. However, when the method is used for many different frequencies and multi-damping ratios, the equations are over constrained and the algorithm may not converge in some cases. In recent works of RSPMatch [24], the convergence problem is addressed, but the fundamental problem of match precision is still unclear.

The main drawback of the previous methods on the ground motion adjustment is lacking the control of its influence to other responses besides peak responses. To overcome this problem, an optimization method is proposed to reduce the match error between response spectra of generated motions and target spectra in this study, in which the influence of the added ground motions on other responses is under control by the constraints in the optimization process. From the optimization view, each adjustment process is effective, and lots of characteristics of the original ground motions are retained through constraining objective variables.

2. The L_∞ norm optimization

In this section, we introduce the main building block of our method, which is an algorithm to solve the problem of L_∞ norm minimization. The algorithm will be employed in the adjustment procedure.

The L_∞ norm of a vector $\mathbf{x}$ is the max absolute value of its components. In quasi-convex programming [33,34], the L_∞ norm minimization problem is in the form of

$$O : \min_{\boldsymbol{x},\gamma} \gamma \tag{1}$$

$$\text{s.t. } \boldsymbol{g}_1(\boldsymbol{x}) - \gamma \boldsymbol{g}_2(\boldsymbol{x}) \preceq \mathbf{0} \tag{2}$$

$$\boldsymbol{x} \in \mathcal{X} \tag{3}$$

$$\gamma \geq 0, \tag{4}$$

where $\boldsymbol{g}_1(\boldsymbol{x}) - \gamma \boldsymbol{g}_2(\boldsymbol{x}) \preceq \mathbf{0}$ is a short form of m inequalities $g_{1i}(\boldsymbol{x}) - \gamma g_{2i}(\boldsymbol{x}) \leq 0,\ \forall i = 1, \ldots, m$. Also, $\boldsymbol{g}_1(\boldsymbol{x})$ is convex and $\boldsymbol{g}_2(\boldsymbol{x})$ is concave. Thus the feasible set $S_\gamma = \{\boldsymbol{x} | \boldsymbol{g}_1(\boldsymbol{x}) - \gamma \boldsymbol{g}_2(\boldsymbol{x}) \preceq \mathbf{0}\}$ is a convex set for fixed γ. Here the minimized L_∞ norm of the vector $(g_{11}(\boldsymbol{x})/g_{21}(\boldsymbol{x}), \ldots, g_{1m}(\boldsymbol{x})/g_{2m}(\boldsymbol{x}))$ corresponds to the solution γ of problem O.

For the classical bisection algorithm on γ, each iteration solves the following convex problem:

$$P_\gamma : \text{ Find } \boldsymbol{x} \tag{5}$$

$$\text{s.t. } \boldsymbol{g}_1(\boldsymbol{x}) - \gamma \boldsymbol{g}_2(\boldsymbol{x}) \preceq \mathbf{0} \tag{6}$$

$$\boldsymbol{x} \in \mathcal{X}. \tag{7}$$

To solve the feasibility problem P_γ, we convert P_γ into Q_γ

$$Q_\gamma : \min_{\boldsymbol{x},w} \quad w \tag{8}$$

$$\text{s.t.} \quad \boldsymbol{g}_1(\boldsymbol{x}) - \gamma \boldsymbol{g}_2(\boldsymbol{x}) \preceq w\mathbf{1} \tag{9}$$

$$\boldsymbol{x} \in \mathcal{X}. \tag{10}$$

Here $\mathbf{1} = (1, \ldots, 1)$ is a vector, of which all the components are equal to 1. The problem Q_γ could be solved by primal-dual interior point methods [35]. Let us use $(\boldsymbol{x}^*, w^*)$ to represent the solution of the problem Q_{γ^*} for a given γ^*. The problem P_{γ^*} is feasible when $w^* \leq 0$, otherwise it is infeasible. Now we are ready to show the complete procedure in Algorithm 1.

Algorithm 1. Bisection algorithm.

Input: Initial interval $[l^1, u^1]$ subject to $l^1 \leq \gamma^* \leq u^1$
while true **do**
  $\gamma_k \leftarrow (l^k + u^k)/2$;
  Solve Q_{γ_k} to get $\mathbf{x}^k$, w;
  if $w < 0$ **then**
    $\mathbf{x}^* \leftarrow \mathbf{x}^k$;
    $u^{k+1} \leftarrow \max_i g_{1i}(\mathbf{x}^k)/g_{2i}(\mathbf{x}^k)$;
    $l^{k+1} \leftarrow l^k$;
  else
    $l^{k+1} \leftarrow \gamma^k$;
    $u^{k+1} \leftarrow u^k$;
  end
  if $u^{k+1} - l^{k+1} < \epsilon$ **then**
    return $(\mathbf{x}^*,\ u^{k+1})$;
  end
end

Although there are some more efficient and complex algorithms to solve the problem O [34,36], we use the classical bisection algorithm for its easier implementation and stability.