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Sensitivity analysis of optimum stochastic nonstationary response spectra under uncertain soil parameters

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Abstract

Local ground characteristics play a fundamental role in seismic design and analysis of structural response. In spite of this, it is usually assumed that these are implicitly deterministic with only few possible values. This work presents a stochastic approach to define response spectra of a single-degree-of-freedom (SDOF) system subjected to a nonstationary seismic action. The ground shaking is here modelled by means of a Clough–Penzien filtered white noise and the mechanical parameters are determined by means of a best fitting procedure. Results are compared with the design Eurocode 8 spectra. Subsequently, a sensitivity analysis with respect to the obtained parameters is performed. It has been developed to evaluate influence of uncertainty in their determination with reference to structural response and to investigate how scattering of parameters could induce variation in response spectra.

The stochastic approach is here considered by solving Lyapunov matrix differential equation in the space state. Typical stiff and soft soils are taken into account, supposing filter parameters to be time invariant. The latter are assumed having a probability density distribution with fixed levels of coefficient of variation (COV) between mean and variance. The developed algorithm achieves tests to verify the efficiency of the proposed approach.

Keywords: Lyapunov equation; Covariance analysis; Stochastic dynamics; Clough–Penzien model; Uncertainty; Design sensitivity; Optimization

1. Introduction

A significant task in the field of civil engineering is the structural response evaluation when dispersion of systems parameters values is considered. The peak response of such a system forced for instance by a seismic load can be deduced considering an established level of probability of exceedance. In the literature (see for example Ref. [1]), uniform hazard spectra (UHS) have been proposed, especially to evaluate the seismic demand under a requested structural reliability. The dynamic analysis is carried out considering that the seismic excitation is characterized by an evolutionary power spectral density function with uncertain parameters, in order to take into account a large set of possible earthquakes. In general, uncertainty of structural problems could be regarding many elements that in conventional structural analysis are assumed deterministic, such as loads intensity or design and geometrical configurations. In many works a typically simplified approach takes place where the implicit source of randomness is assumed to be in dynamic loads characterized by a stochastic nature, as in case of earthquake or wind actions. They can be accurately modelled by stochastic process, and the standard random vibration theory can be used if all the other motion equations parameters are supposed deterministic. As a consequence, this kind of approach gives structural response characterization completely described by stochastic processes with deterministic parameters.

Moreover, the scientific interest in this kind of problem, is acquiring increasing importance in last decade for example in the field of classical optimization methods or to evaluate buildings' performances when some design variable has changed; this issue was examined by some authors who used various methodologies to consider the scattering of parameters: Igusa and Der Kiureghian [2] used perturbation theory while Chaudhuri and Gupta [3]

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Nomenclature

k	structural stiffness
c	structural damping
T_s	structural period
ω_f, ξ_f	first filter frequency and damping ratio
ω_p, ξ_p	second filter frequency and damping ratio
ω_s, ξ_s	structural frequency and damping ratio
$\ddot{X}_f(t)$	first filter acceleration
$\ddot{X}_p(t)$	second filter acceleration
$\ddot{X}_s(t)$	relative structural acceleration
$\ddot{Y}_s(t)$	inertial structural acceleration
$\dot{X}_f(t)$	first filter velocity
$\dot{X}_p(t)$	second filter velocity
$\dot{X}_s(t)$	structural velocity
$X_f(t)$	first filter displacement
$X_p(t)$	second filter displacement
$X_s(t)$	structural displacement
PGA	peak ground acceleration
$W(t)$	white noise process
S_0	intensity of the white noise
$\varphi(t)$	white noise modulation function
$\overline{Z}(t)$	space state vector
$\mathbf{A}$	system matrix in the space state
$\overline{F}(t)$	input forcing vector
$\mathbf{R}_{ZZ}$	covariance matrix
$\mathbf{G}(t)$	matrix of Lyapunov equation
$\sigma_{X_s}(t)$	standard deviation of process $X_s(t)$
$\sigma_{\dot{X}_s}(t)$	standard deviation of process $\dot{X}_s(t)$
$\gamma_{X_s\dot{X}_s}$	cross-covariance between X_s and $\dot{X}_s$
$v^+(t)$	average rate of up-crossing a level α
r	structural reliability
P_f	probability of failure
p^*	peak factor
S_d	displacement spectrum
S_a	acceleration spectrum
$\overline{b}$	uncertain parameters vector
$\overline{\rho}$	coefficient of variation (COV)

assumed an uncertainty regarding the shear wave velocity and Poisson's ratio of foundation soil. They considered that the two parameters were independent and characterized by a Gaussian distribution; then, performing a mode-acceleration formulation in the frequency domain for a multi-degree-of-freedom system constituted by a combined primary and secondary structure, they noted that the variation in shear wave velocity has no remarkable effect on dynamic response in the case of a little interaction between soil and structure. On the other hand, uncertainty in Poisson's ratio has an appreciable effect only if soil damping is sensitive to it and a considerable interaction between soil and structure occurs. Another interesting approach was proposed by Chaudhuri and Chakraborty [4]: in their work an innovative methodology in calculating the response sensitivity evaluation of structures in seismic reliability evaluation was proposed. In fact, in order to perform such analysis the knowledge of response gradients with respect to loading and design parameters are essential. They considered a multi-storey building frame in finite element modelling: depths of columns and beams are considered as design parameters to accomplish the desired sensitivity analysis. Recently, a semi-analytical approach to evaluate the sensitivity of the stochastic response of both classically and nonclassically damped structural systems subjected to stationary and nonstationary stochastic Gaussian excitation has been presented [5]. The equations that govern the sensitivity of two statistical moments of the response are derived firstly in the time domain by using the Kronecker algebra and a modal expansion of response is selected. Finally, an innovative approach [6] that minimizes computational effort in design sensitivity in large structural systems with many design variables was proposed. The authors utilize an approximate re-analysis to improve the efficiency of dynamic sensitivity analysis; using modal space, the response derivatives with respect to design variables are presented as a combination of sensitivities of the eigenvectors and the generalized displacements. A procedure intended to reduce the number of differential equations that must be solved during the solution process is proposed. Efficient evaluation of the derivatives, using finite difference and combined approximations approach, is presented. Numerical examples conducted on a cantilever column and on a five-story frame show that high accuracy of design sensitivities can be achieved efficiently.

The main intention of this work is to evaluate the peak covariance response (in terms of displacement and acceleration) in the time domain, solving the well-known Lyapunov matrix differential equation, and the curves that enclose its possible variation. To realize this study, a linear stochastic single-degree-of-freedom (SDOF) system is considered subjected to a nonstationary seismic load. This input is modelled by a Clough–Penzien oscillator subjected to a coloured white noise that in most cases fits well to represent a wide class of stochastic loads, especially earthquakes. In many works, however, Kanai-Tajimi modelling is selected [7], but it has been demonstrated (see, for example, Ref. [8]) that this model is too poor to represent real seismic motion because of the presence of only two filter parameters and is not so able to represent ground motion from medium to large structural periods. The problem with Clough–Penzien approach, although quite accurate from a mathematical point of view, is that the parameter values presented in the literature seem incongruous with respect to current design codes and between proposals of different authors. To realize this matching an optimization procedure that fits the response spectra with Eurocode 8 is initially performed. Then, the sensitivity of covariance response with respect of soil parameters is attained. More specifically the sensitivity is