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Stochastic optimal design of nonlinear viscous dampers for large-scale structures subjected to non-stationary seismic excitations based on dimension-reduced explicit method

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ABSTRACT

Nonlinear fluid viscous dampers have been widely used in energy-dissipation structures. This paper is devoted to the stochastic optimal design of viscous dampers for large-scale structures under non-stationary random seismic excitations. The optimization problem is formulated as the minimization of the standard deviation of a target displacement component subjected to the constraint on the standard deviations of damping forces of viscous dampers, and the method of moving asymptotes (MMA), a gradient-based optimization method, is employed to solve the optimization problem involved. An effective dimension-reduced explicit method is first proposed for fast nonlinear time-history analysis of structural responses and the corresponding sensitivity analysis with respect to the parameters of viscous dampers, in which only a small number of degrees of freedom associated with the viscous dampers need to be considered in the iteration scheme, leading to extremely low computational cost in the nonlinear analysis. Then the proposed dimension-reduced explicit method is further used to conduct sample analyses with high efficiency in Monte-Carlo simulation (MCS) so as to obtain the statistical moments of critical responses and the relevant moment sensitivities required in the process of optimal design. To demonstrate the feasibility of the proposed method, the stochastic optimal design of viscous dampers is carried out for a large-scale suspension bridge with a main span of 1688 m, and the mean peak values of critical responses with the optimal parameters of viscous dampers are finally obtained for the design purpose of the bridge.

1. Introduction

The control of structural vibrations produced by earthquakes can be carried out by providing active or passive counter forces [1–3]. For active control of structures, Li et al. [4,5] recently proposed a novel stochastic optimal control scheme based on the probability density evolution method [6]. Zhu and his co-authors [7,8] developed a stochastic optimal control strategy for nonlinear systems with actuator saturation based on the stochastic averaging method and stochastic dynamical programing principle. On the other hand, passive control techniques have also received considerable attention and have been widely applied to civil structures. Among various means of passive control, energy-dissipation devices are frequently employed to absorb a portion of earthquake-induced energy so as to reduce energy dissipation demand on primary structural members and minimize possible structural damage. The use of supplemental energy-dissipation systems has proven to be an effective approach for enhancing structural performance against seismic hazard [9].

To obtain a better performance of structural control, the parameters of energy-dissipation devices need to be determined through optimal design procedures. In engineering practice, deterministic structural optimization techniques are usually used to obtain the device parameters under seismic excitations [10–15]. However, due to the intrinsic uncertainties of ground motions, deterministic structural optimization cannot capture the optimal performance of energy-dissipation structures from a probabilistic point of view. Therefore, stochastic optimal design methods are required to take into account the stochastic nature of earthquakes. Ni et al. [16] conducted a parametric study on the optimal parameters, positions and numbers of the nonlinear hysteretic damping devices connecting two adjacent buildings exposed to stationary random seismic excitations. Basili and De Angelis [17] dealt with the problem of optimal passive control based on parametric studies on coupled structures with nonlinear hysteretic connections using a simple two-degrees-of-freedom model subjected to stationary white-

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noise and filtered white-noise seismic excitations. Ok et al. [18] used the genetic algorithm to investigate the optimal design of nonlinear hysteretic dampers connecting two adjacent structures under ground motion modelled as stationary filtered white-noise. Martínez et al. [19] employed a sequential quadratic programming procedure to optimally define the locations and sizes of nonlinear hysteretic dampers on planar structures to meet an expected level of performance under stationary seismic excitations.

It can be seen from the above literatures that the stochastic optimal designs of nonlinear damping devices were primarily limited to the problems of stationary seismic excitations. However, seismic excitations are in essence non-stationary random processes, and thus non-stationary random vibration analysis should be taken into consideration. Spanos and his co-authors have made much progress towards determining the evolutionary stochastic response of nonlinear systems [20–23], and recently Kougioumzoglou et al. [24,25] have also proposed the Wiener path integral technique for non-stationary stochastic response analysis of nonlinear systems. As for the stochastic optimal design of energy-dissipation structures, only few works were presented in the literatures involving non-stationary seismic excitations. Jensen and Sepulveda [26] proposed a reliability-based optimal design approach for a four-storey reinforced concrete building with hysteretic energy dissipators under ground motion modelled as non-stationary stochastic process, in which subset simulation (SS) was employed to solve the reliability problem involved. Altieri et al. [27] also proposed a robust reliability-based optimization tool with SS for the design of viscous coefficients of nonlinear dampers of a three-storey steel building frame by modeling the non-stationary seismic input through a stochastic ground motion model. Gidaris and Taflanidis [28] carried out a life-cycle cost based optimal design of nonlinear viscous dampers in a three-storey office building subjected to non-stationary ground motion, and the probabilistic quantities required in the optimization process were calculated through Monte-Carlo simulation (MCS). In the above three references, the repetitive sample analyses involved in the stochastic simulation were conducted using the traditional nonlinear time-history analysis method, which would be time-consuming for large-scale engineering structures.

The optimization algorithms can be categorized as either non-gradient-based algorithms or gradient-based algorithms. The non-gradient-based algorithms, for instance, the genetic algorithm, are primarily used for global optimization problems with a large number of function evaluations, and therefore they are impractical for optimization of real engineering structures [29]. The gradient-based algorithms are in general more efficient for high-dimensional, nonlinear constrained and convex optimal problems [30]. A variety of gradient-based algorithms, including the sequential linear programming methods, the sequential quadratic programming methods and the convex approximation methods, are available for solving optimization problems [31]. In particular, the method of moving asymptotes (MMA) [32], one of the convex approximation methods, has been proven to be an appropriate approach to solve structural optimization problems, and therefore it is employed in the present study for optimal design of energy-dissipation structures.

In recent years, Su and his co-authors have proposed and developed an explicit time-domain method [33–35], which is mainly devoted to solving non-stationary random vibration problems of linear and nonlinear large-scale structures. On this basis, an efficient dimension-reduced explicit method is proposed in this study for stochastic optimal design of nonlinear viscous dampers of energy-dissipation structures under non-stationary seismic excitations. The optimization problem is formulated as the minimization of the standard deviation of a target displacement component subjected to the constraint on the standard deviations of damping forces of viscous dampers, and then the MMA is used to solve the stochastic optimal problem involved. The non-stationary random responses and their sensitivities with respect to design variables required in the process of optimal design are obtained using MCS with the high efficient dimension-reduced explicit method. To illustrate the accuracy and efficiency of the present approach, stochastic optimal design of viscous dampers for a suspension bridge with a main span of 1688 m is conducted, and the mean peak values of critical responses of the bridge are also obtained with the optimal parameters of viscous dampers.

2. Nonlinear time-history analysis based on dimension-reduced explicit iteration scheme

2.1. Time-domain explicit expressions of dynamic responses

For a multi-degree-of-freedom energy-dissipation structure equipped with n nonlinear viscous dampers subjected to seismic excitations, the nonlinear equation of motion can be expressed as

$$\mathbf{M}\ddot{\mathbf{U}} + \mathbf{C}\dot{\mathbf{U}} + \mathbf{K}\mathbf{U} + \mathbf{F}_{\mathrm{D}}(\dot{\mathbf{U}}_{\mathrm{D}}) = -\mathbf{M}\mathbf{E}X(t) \tag{1}$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ denote the mass, damping and stiffness matrix of the structure without viscous dampers, respectively; $\mathbf{U}$, $\dot{\mathbf{U}}$ and $\ddot{\mathbf{U}}$ denote the time-dependent nodal displacement, velocity and acceleration vector of the energy-dissipation structure, respectively; $\mathbf{E}$ denotes the orientation vector of the seismic excitation; $X(t)$ denotes the ground motion acceleration; $\dot{\mathbf{U}}_{\mathrm{D}}$ denotes the velocity vector of the nodes of viscous dampers; and $\mathbf{F}_{\mathrm{D}}(\dot{\mathbf{U}}_{\mathrm{D}})$ denotes the nonlinear damping force vector of viscous dampers, which can be written as

$$\mathbf{F}_{\mathrm{D}}(\dot{\mathbf{U}}_{\mathrm{D}}) = \mathbf{E}_1 f_1(t) + \mathbf{E}_2 f_2(t) + \cdots + \mathbf{E}_n f_n(t) \tag{2}$$

where $f_k(t)$ $(k = 1, 2, \cdots, n)$ is the nonlinear damping force of the kth viscous damper, and $\mathbf{E}_k$ is the orientation vector of the kth nonlinear damping force.

The nonlinear damping force-velocity relation for fluid viscous dampers can be analytically expressed as a fractional velocity power law [36]

$$f(t) = \mathrm{sign}(v)c|v|^{\alpha} \tag{3}$$

where $f(t)$ denotes the damping force of the viscous damper; $\mathrm{sign}(\cdot)$ denotes the sign function; v denotes the nodal relative velocity between damper ends; and c and α denote the damping coefficient and the velocity exponent of the viscous damper, respectively. Since the constitutive law of fluid viscous dampers is highly nonlinear, the whole system has inherent nonlinear properties even if the structure behaves linearly [37,38].

Moving the nonlinear damping force vector $\mathbf{F}_{\mathrm{D}}(\dot{\mathbf{U}}_{\mathrm{D}})$ to the right-hand side of Eq. (1), one can obtain the following quasi-linear equation of motion as

$$\mathbf{M}\ddot{\mathbf{U}} + \mathbf{C}\dot{\mathbf{U}} + \mathbf{K}\mathbf{U} = \mathbf{L}\mathbf{F}(t) \tag{4}$$

where

$$\mathbf{F}(t) = [X(t) \quad f_1(t) \quad f_2(t) \cdots f_n(t)]^{\mathrm{T}} \tag{5}$$

and

$$\mathbf{L} = -[\mathbf{M}\mathbf{E} \quad \mathbf{E}_1 \quad \mathbf{E}_2 \cdots \mathbf{E}_n] \tag{6}$$

Evidently, $\mathbf{F}(t)$ is composed of the ground motion acceleration and the nonlinear damping forces associated with all the viscous dampers, and therefore is termed as the equivalent excitation vector for the quasi-linear equation of motion. $\mathbf{L}$ is the corresponding orientation matrix of $\mathbf{F}(t)$.

For the quasi-linear equation of motion shown in Eq. (4), define the state vector as $\mathbf{V} = [\mathbf{U}^{\mathrm{T}} \ \dot{\mathbf{U}}^{\mathrm{T}}]^{\mathrm{T}}$. Then, the recurrence formula for the state vector can be written as

$$\mathbf{V}_i = \mathbf{T}\mathbf{V}_{i-1} + \mathbf{Q}_1\mathbf{F}_{i-1} + \mathbf{Q}_2\mathbf{F}_i \quad (i = 1, 2, \cdots, l) \tag{7}$$

where l is the number of time steps for time-history analysis; $\mathbf{V}_i$, $\mathbf{V}_{i-1}$, $\mathbf{F}_i$ and $\mathbf{F}_{i-1}$ denote $\mathbf{V}(t_i)$, $\mathbf{V}(t_{i-1})$, $\mathbf{F}(t_i)$ and $\mathbf{F}(t_{i-1})$, respectively, with $t_i = i\Delta t$, $t_{i-1} = (i-1)\Delta t$ and Δt being the time step; and $\mathbf{T}$, $\mathbf{Q}_1$ and $\mathbf{Q}_2$ can