Engineering Structures 81 (2014) 256–264

Contents lists available at ScienceDirect

Engineering Structures

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

Integrated structure-passive control design of linear structures under seismic excitations

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ARTICLE INFO

Article history:
Received 9 November 2013
Revised 30 September 2014
Accepted 1 October 2014

Keywords:
Integrated design
Optimal design
Passive energy dissipation system

ABSTRACT

For purpose of enhancing the seismic performance of civil structures, external passive energy dissipation systems have been extensively used. Usually, the energy dissipation system is provided once the structure has been designed. Obviously, a sequential procedure cannot lead to the best overall design. In this paper, a simultaneous integrated design of the structure and passive control system is formulated as a two-objective optimization problem. As in almost all optimization problems with conflicting objective functions, in this study, different optimal solutions (efficient designs) that meet required restrictions are obtained. Since, the stochastic structural response is obtained in the frequency domain from the power spectral density function of the excitation, the proposed approach is very efficient, robust and requires considerably less computational effort than time history analysis. The methodology is demonstrated through a numerical example on a shear-type framed building.

1. Introduction

For purpose of enhancing the seismic performance of civil structures, external passive energy dissipation systems have been extensively used [1,2]. Traditionally, the process of designing a structure and its passive vibration control system has been sequential and obviously it cannot lead to the best overall design. In general, an energy dissipation system is optimally designed to improve the seismic performance after the structure has been initially designed under constraints on weigh, strength and displacements [3,4]. However, because of the coupling between the structure and control system, a simultaneous integrated design of both leads to a better performance (optimal solution) than a sequential design [5–7]. Reyer [6] formally classified the various optimization strategies into sequential, iterative, bi-level (nested), and simultaneous. A comparison between those strategies was also conducted by the author. Early works regarding sequential design were conducted by Khot et al. [8], and Venkayya and Tischler [9]. To improve the optimality level of sequential strategies, Grigiriadis et al. [10] and Smith et al. [11] proposed iterative strategies which consist of first, improving the structure design without compromising the control performance then, optimizing the controller without compromising the structural performance and so on until the tolerance is reached. Bi-level strategies are based on two nested optimization loops. The outer loop optimizes a scalar objective function which is a linear combination of two objective functions, one related to the structure and the other one to the controller, by varying only the structural design. In the inner loop an optimal controller for each structure selected by the outer loop is generated [12,13]. Finally, simultaneous optimization involves finding the optimal system design by solving the same scalar objective function of the previous case, but changing the design parameters of both structure and controller [14–17]. This strategy usually involves a complex non-convex mathematical problem. Fathy et al. [18] showed rigorously that system-level optimally is guaranteed with the nested and simultaneous strategies, but not with the sequential o iterative strategies. In the aerospace industry, integrated optimal design of structural-control systems has had a great development in the last 30 years as is evident from previous references; however, in civil engineering applications, there is still a widespread resort to traditional (sequential) design [19–21]. Most woks in the literature address the integrated design of the structure combined with an active control system and only a few with a passive control system. A simultaneous integrated design of the structure-control system from a composite objective function introduced as a linear combination of structural and active control objective functions was presented by Salama et al. [22]. A formal optimization procedure has been developed by Chattopadhyay and Seeley [23] which addresses the optimal locations of piezoelectric actuators and structural parameters. An algorithm used to minimize multiple and conflicting

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http://dx.doi.org/10.1016/j.engstruct.2014.10.002
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objective functions associated with the coupled design of both, structure and active control system is introduced by Cheng [24]. On two structural design examples, Pareto optimal solutions were obtained. Rao et al. [25] presented a procedure similar to that Cheng [24], but applied on two truss structures. Khot [26] proposed a method to simultaneously design structure-control system to suppress structural vibrations due to external disturbances using a multi-objective optimization approach based on global criteria. A two-stage procedure for a controlled structural system design was presented by Cimellaro et al. [27]. The methodology is based on a redesign of the structure for better controllability by modifying the linear structural system (mass, stiffness and damping) and reducing the active control power. Similar approach, but applied to inelastic structures is described in Cimellaro et al. [28].

Few researchers treated the problem that simultaneously evaluates stiffness and added passive damping of linear structural systems subjected to seismic o random excitations. Takewaki [29] introduce a design problem to minimize the sum of relative story displacements to stationary random excitation subjected to a constraint on the sum of the stiffness and damping coefficients. Park et al. [30] described an approach for an integrated optimal design of a viscoelastically damped structural system. Optimization problem is formulated adopting as design variables, the amount and locations of the viscoelastic dampers. To solve the optimization problem, a genetic algorithm is used as a numerical searching technique. On the other hand, Cimellaro [31] proposed a procedure based on a generalized objective function defined by a linear combination of the norm of displacement, acceleration and base shear transfer functions evaluated at the updated fundamental natural frequency constrained by the total stiffness and damping.

For providing assistance to the structural engineer (decision-maker), in the present work, a simultaneous integrated design of the structure and passive control system formulated as a two-objective optimization problem is proposed. The outstanding point of the procedure described in the study is to have chosen the total story stiffness and the total story damping as conflicting-objective functions. In general, by reducing stiffness, the absolute acceleration and consequently the base shear decrease, but at the expense of an increase in the displacements; on the other hand, by increasing the energy dissipation, the relative displacements are reduced with little or no increase in the absolute acceleration [31,32]. Thus, the procedure gives a broad overview of different Pareto-optimal solutions (designs) that meet a required structural performance, and enables to select the best compromise solution as a trade-off between stiffness and added damping. Knowing that the main contribution to the total uncertainty is due to the excitation and with the aim of achieving robust results, the most appropriate approach to model the excitation is through a stationary stochastic process characterized by a power spectral density function compatible with the response spectrum defined by the seismic code provisions. Since the maximum structural response is estimated in the frequency domain through stochastic vibration theory, this approach is more efficiently and requires considerably less computational effort than time history analysis. From the results on a symmetrical building modelled as a linear shear-type planar frame it is found that through the proposed procedure, different efficient designs can be reached maintaining the required level of structural performance.

2. Formulation of the integrated design problem

As mentioned before, the integrated design problem of the structure and the passive control system is formulated as a two-objective optimization problem expressed as follows:

Find $\boldsymbol{z}$ that minimizes the following objective function vector:

$$\boldsymbol{f}(\boldsymbol{z}) = \{f_1(\boldsymbol{z}), f_2(\boldsymbol{z})\} \tag{1}$$

subjected to

$$g_i(\boldsymbol{z}) \leqslant 0, \quad i = 1, 2, \ldots, p$$

$$u_i(\boldsymbol{z}) = 0, \quad i = 1, 2, \ldots, q$$

in which $\boldsymbol{z}$ is the design variable vector, $f_1(\boldsymbol{z}), f_2(\boldsymbol{z})$ are the objective functions and $g_i(\boldsymbol{z})$, $u_i(\boldsymbol{z})$ are the constraint functions.

The main characteristic of the two-objective optimization problem is that none of the feasible solutions allow simultaneously minimizing both objective functions. To overcome this problem a Pareto-optimal solution is useful and defined as [33]: if vector $\boldsymbol{z}^p$ is a solution of Eq. (1), there exists no feasible vector $\boldsymbol{z}$ that would decrease same objective function without causing a simultaneous increase in, at least, other objective function. Usually several Pareto-optimal solutions exist for a vector optimization problem and to select the best solution, the designer judgment alongside additional information are needed. There are several methods for solving a vector optimization problem. The most commonly used approach, known as the weighting method, substitutes the vector optimization problem Eq. (1) into a scalar one formulated as a weighted sum of the individual objective functions as:

$$F(\boldsymbol{z}) = w_1 f_1(\boldsymbol{z}) + w_2 f_2(\boldsymbol{z}) \tag{2}$$

in which w_1 and w_2 are weighting factors.

A set of Pareto-optimal solutions denoted as $\{\boldsymbol{z}^{\boldsymbol{p}}\}$ can be generated by varying the weight of each objective function. In order to select the best solution, the designer should previously define the weight of each objective function from additional information (cost, feasibility, etc.), or resort to a decision-making process [34,35]. In this study, besides displaying the set of Pareto-optimal solutions, the following decision-making process is adopted. In a cooperative optimization procedure, the best solution should guarantee that each objective function reaches the lowest possible value, even if it is not its own minimum value. For this, an optimal solution $\boldsymbol{z}_{\boldsymbol{k}}^{*}(k = 1,\ 2)$ minimizing ***individually*** to each objective function is obtained subjected to the constraints stated in Eq. (1). Then, a matrix $\boldsymbol{P}$ can be constructed as:

$$\boldsymbol{P} = \begin{bmatrix} f_1(\boldsymbol{z}_1^*) & f_2(\boldsymbol{z}_1^*) \\ f_1(\boldsymbol{z}_2^*) & f_2(\boldsymbol{z}_2^*) \end{bmatrix} \tag{3}$$

in which, the lowest values of each objective functions, $f_{k,min} = f_k(\boldsymbol{z}_k^*)$, are in the diagonal elements of matrix $\boldsymbol{P}$ and the highest ones outside of it, $f_{k,max} = max[f_k(\boldsymbol{z}_j^*)],\ k \neq j\ k,\ j = 1, 2$. During cooperative optimization, the *k-th* objective function should never have a value lower than $f_{k,min}$ (if the problem is well-defined), nor should it exceed $f_{k,min}$ (it runs counter to the objective of minimizing f_k). Based on these assertions, the following objective function can be constructed:

$$R = \prod_{k=1}^{2} \frac{[f_{k,max} - f_k(\boldsymbol{z}^{\boldsymbol{p}})]}{[f_{k,max} - f_{k,min}]} \tag{4}$$

in which, the range of R is $0 < R < 1$ and $\boldsymbol{z}^{\boldsymbol{p}}$ denotes a Pareto-optimal solution minimizes to Eq. (2).

Therefore the solution $\hat{\boldsymbol{z}}$ selected from Pareto-optimal set, $\{\boldsymbol{z}^{\boldsymbol{p}}\}$, which maximizes R, is the best solution (rational compromise solution).

2.1. Objective functions and constraints

In any structural design, the aim is to guarantee a required level of structural performance at the lowest possible total cost. Assuming that non-structural live and dead floor masses are defined by operational requirements, the total cost is associated with the structural stiffness and the size of energy dissipation system. Without limiting the applicability of the methodology to any type of