Engineering Structures 69 (2014) 135–148

Contents lists available at ScienceDirect

Engineering Structures

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

Optimal design of semi active control for adjacent buildings connected by MR damper based on integrated fuzzy logic and multi-objective genetic algorithm

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ARTICLE INFO

Article history:
Received 3 June 2013
Revised 7 March 2014
Accepted 11 March 2014
Available online 12 April 2014

Keywords:
Adjacent buildings
Semi-active control
Clipped-optimal algorithm
Magneto-rheological (MR) damper

ABSTRACT

An optimal design strategy based on genetic algorithms (GA) is proposed for nonlinear hysteretic control devices that prevent pounding damage and achieve the best results in seismic response mitigation of two adjacent structures. An integrated fuzzy controller is used in order to provide the interactive relationships between damper forces and input voltages for MR dampers based on the modified Bouc-Wen model. Furthermore, Linear Quadratic Regulator (LQR) and H_2/LQG (Linear Quadratic Gaussian) controllers based on clipped voltage law (CVL) are also used to compare the results obtained by fuzzy controller. This study employs the main objectives of the optimal design that are not only to reduce the seismic responses but also to minimize the total cost of the damper system. A set of Pareto optimal solutions is also conducted with the corresponding results obtained from the optimal surface of Pareto solutions in this study. As a result, decreasing the number of dampers does necessarily increase the efficiency of the system. In fact, reducing the number of dampers for the dynamic response of the system can contribute more than increasing the number of dampers.

1. Introduction

In structural design it is necessary that the total displacement and the inter-storey drift of the structures should be limited whereas the absolute acceleration must be kept small for the human comfort. Structures with installed fluid visco-elastic dampers (VEDs) [1–4], friction dampers [1–5], active devices [6–9] and semi-active magnetorheological (MR) dampers [10–13] systems have been introduced for the human comfort in today's modern concepts. The control systems that are optimized using the procedures developed in previous studies [14–16] are capable of mitigating the response of the structure. Several types of dampers have been studied onto structures as paramount interest over the past two decades. Despite high-rise buildings being constructed in close proximity, various methodologies of interconnecting adjacent buildings have been examined for seismic hazard mitigation. Despite the development of recent control strategies like semi-active control, research in the area of passive and active structural control is still continuing [17].

According to stochastic response of the building in the parametric study of Kim et al. [18], there is a certain size of fluid visco-elastic dampers to minimize the response of the structures subject to white noise and earthquake excitation. In recent years, owing to the adaptability of semi-active control devices, considerable attention has been directed to research and development. One such innovative device is the magnetorheological (MR) damper, which utilizes MR fluids for providing control capability. A MR damper offers a highly reliable mechanism for response reduction at a modest cost, and is fail-safe because the damper becomes passive if the control hardware breaks down [19]. Dyke et al. [20], Ni et al. [21], Park and Ok [22] and Kim and Kang [23] have investigated the effectiveness of MR dampers for civil engineering structures. A wide range of theoretical and experimental studies of a 20-tonne MR damper at the University of Notre Dame have demonstrated that MR devices can provide forces of the magnitude required for full-scale structural control applications [24].

For the optimization of damper parameters, Luco and De Barros [25] investigated the optimal damping values for the distribution of passive dampers. In general, analytical and experimental studies have investigated the dynamic responses of the structures before and after installing a damping device to understand their effectiveness. However, very little study has been done with regard to the effect of non-uniform distribution of the dampers [3,6,14,15]. None of these studies show a clear comparison so as to signify the quality of their own proposed arrangement/solution. For example,

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http://dx.doi.org/10.1016/j.engstruct.2014.03.006

Bhaskararao and Jangid [6] proposed a parametric study to investigate the optimum slip force of the dampers in the responses of two adjacent structures. The authors also confirmed that the response reduction is associated with optimum placement of dampers. Yang et al. [3] showed that in order to minimize loss in performance the number of dampers can be decreased. The authors showed that it is not necessary to equip every single floor with a viscous damper in accordance with the solution of trial and error. But no solution for the optimal arrangement was provided.

A similar study for MR dampers conducted by Bharti et al. [15] proposed that the placement of damper is not necessary for every single floor. Bharti et al. [15] also confirmed the results obtained by Ok et al. [14] which studied the performance of adjacent buildings equipped with MR dampers by the use of genetic algorithms. As an attempt to bring a clear method to provide the optimal arrangement, Bigdeli et al. [26] introduced optimization algorithms to find the optimal configuration for a given number of dampers. For the purposes of comparison, the authors also used the highest relative velocity heuristic approach based on the work of Uz [27]. Uz and Hadi [28,29] proposed that fluid viscous dampers should be placed in floors where the maximum relative velocity occurs. This work was repeated by Patel and Jangid [30].

For developing other recent control strategies, various control algorithms developed for passive, semi-active and active control have been directly useful. The most common optimal control algorithms such as Linear Quadratic Regulator (LQR), H_2/LQG (Linear Quadratic Gaussian), H_2, H_∞ and the FLC theory can be chosen with combining the GAs. The fuzzy logic control (FLC) theory has attracted the attention of engineers during the last few years [16,31], there are some drawbacks in FLC systems. The fuzzy sets and rules that require a full understanding of the system dynamics must be correctly pre-determined for the system to function properly. Furthermore, in order to mitigate the responses of a seismically subjected civil engineering structures, multiple MR dampers distributed between the adjacent buildings should be used [16]. Zhou et al. [32] successfully applied an adaptive fuzzy control strategy for control of linear and nonlinear structures. The authors found that the adaptive feature of a fuzzy controller has various advantages in the control of a building including a MR damper system.

Another trend in the development of a FLC system is to combine genetic algorithms (GA) as an optimization tool in designing control systems [26,33–39]. Optimizing the dampers to mitigate seismic damage for adjacent buildings has hitherto not been investigated well in spite of enhancing structural control concepts in the structural vibration control through the application of optimization in an integrated genetic algorithm (GA)–FLC. Based on the improvements in the fuzzy logic controller for multiple mode contributions, nonlinear base isolated structures using semi active devices together with passive devices in a hybrid manner were investigated in order to utilize a set of bench mark problems [40,41]. Ahlawat and Ramaswamy [42] proposed an optimum design of dampers using a multi-objective version of the GA. Arfiadi and Hadi [36] improved a simple optimization procedure with the help of GAs to design the control force. They used a static output feedback controller utilizing the measurement output. For obtaining the best results in the reduction of the structures, combined application of the GAs and FLC has been proposed to design and optimize the different parameters of active dampers by Pourzeynali et al. [43].

In this study, the optimal design of semi-active dampers placed between adjacent buildings is investigated into two different sections. In the first section, an adaptive method for the design of a FLC system for protecting adjacent buildings under dynamic hazards using MR dampers is proposed by using single GA. The design of the genetic adaptive fuzzy (GAF) controller is described in the first section of this study. Minimizations of the peak inter-storey drift and displacement related to ground responses are the two objectives of this study. A global optimization method which is a modification of the binary coded genetic algorithm adopted by Arfiadi and Hadi [35,36] has been used. Binary coded GA is used to derive an adaptive method for selection of fuzzy rules of the FLC system. The fuzzy correlation between the inputs (structural responses) and the outputs (command voltages) of the controller is provided with adding, changing and deleting the rules of the FLC system. Inputs are taken as the top floor displacements of both buildings. Nevertheless, the binary coded GA automatically employs and optimizes the fuzzy controller in accordance with the fitness function that reflects the multiple objectives. The last section presents results of this study which show that not only there is a reduction of seismic responses of the adjacent buildings but also the total cost of the damper system is reduced. Therefore, the peak inter-storey drift response and the total number of nonlinear dampers constitute the objective functions of the optimization problem for two buildings.

This study uses two groups of design variables of the optimization. The first group of variables relate to whether a damper exists or not between each of the floors of the buildings. Cleary these floors relate to the shorter building. In order to achieve the objectives of this study, dampers are proposed to be installed between the two buildings of each floor up to the top floor of the shorter building. The existence of these dampers and their corresponding voltages are design variables of this study. The design process uses the excitations of the NS components of the El-Centro 1940 and Kobe 1995 ground acceleration records. Numerical results of adjacent buildings controlled with MR dampers and the corresponding uncontrolled result are examined and compared with nonlinear control algorithms.

2. System description

Two n and m storey shear buildings with semi-active dampers installed between them as shown in Fig. 1 are considered. With combining integrated fuzzy logic and GA, the top floor displacements of the adjacent buildings are used as the inputs of a fuzzy controller. The fuzzy controller outputs command voltages in order to control MR dampers for generating damping force.

$$\Lambda = \begin{bmatrix} P_1 \\ 0 \\ P_2 \end{bmatrix}, \quad \Gamma = \begin{bmatrix} -M_1 E_1 \\ -M_2 E_2 \end{bmatrix}, \quad A = \begin{bmatrix} 0_{(n+m)\times(n+m)} & \mathbf{I}_{(n+m)\times(n+m)} \\ -M^{-1}K & -M^{-1}C \end{bmatrix}$$
$$E = \begin{bmatrix} 0_{(n+m)\times 1} \\ M^{-1}\Gamma \end{bmatrix}, \quad B = \begin{bmatrix} 0_{(n+m)\times n_a} \\ M^{-1}\Lambda \end{bmatrix} \tag{1}$$

where E_1 and E_2 are $n \times 1$ and $m \times 1$ unity matrices, respectively. P_1 and P_2 are given as $m \times n_a$ matrices based on the number of actuators of the additional dampers (n_a). m denotes the storey number of the lower building. Here, $\mathbf{I}$ is an identity matrix and 0 in Λ matrix is a $(s \times n_a)$ matrix containing zero. $F_{mr} = [f^1_{mr} \quad \ldots \quad f^i_{mr} f^m_{mr}]^T$ is control input vector. The equation of motion in Eq. (1) can be arranged as

$$\dot{X} = AX + BF_{mr}(t) + EX_g(t) \tag{2}$$

As mentioned above, the control objective in single objective GA is to minimize both the peak displacement and inter-storey drift responses of the adjacent buildings to provide safety of both buildings and maintain an acceptable level of comfort for the occupants.

2.1. MR damper forces

For the first time, Spencer Jr et al. [44] presented the MR dampers force through applying the Bouc-Wen model. The modified