Engineering Structures 41 (2012) 242–257

Contents lists available at SciVerse ScienceDirect

Engineering Structures

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

Semi-active fuzzy control of a wind-excited tall building using multi-objective genetic algorithm

Hyun-Su Kim [a], Joo-Won Kang [b,*]

[a] Division of Architecture, Sunmoon University, Asan-si, Republic of Korea
[b] School of Architecture, Yeungnam University, Gyeongsan-si, Republic of Korea

ARTICLE INFO

Article history:
Received 7 July 2011
Revised 19 March 2012
Accepted 21 March 2012
Available online 28 April 2012

Keywords:
Multi-objective genetic algorithms
Wind-induced response control
Semi-active tuned mass damper
MR damper
Fuzzy logic control system
Tall building

ABSTRACT

In this study, a multi-objective optimal fuzzy control system for the response reduction of a wind-excited tall building has been proposed. A semi-active tuned mass damper (STMD) is used for vibration control of a 76-story benchmark building subjected to wind load. An STMD consists of a 100 kN magnetorheological (MR) damper and its natural period is tuned to the first-mode natural period of vibration of the example building structure. The damping force of the MR damper is controlled by a fuzzy logic controller. A multi-objective genetic algorithm is used for optimization of the fuzzy logic controller. Both the 75th floor acceleration response of the structure and the stroke of the STMD have been used as the objective functions for this multi-objective optimization problem. Because a multi-objective optimization approach provides a set of Pareto-optimal solutions, an engineer is able to select an appropriate design for the specific performance requirement. For a comparative study, a sky–ground hook control algorithm is employed for control of the STMD. Based on numerical results, it has been shown that the proposed control system can effectively reduce the STMD motion as well as building responses compared to the comparative sky–ground hook control algorithm. In addition, the control performance of the STMD controlled by the optimal fuzzy controller is superior to that of the passive TMD and is comparable to an active TMD, but with a significant reduction in power consumption.

1. Introduction

One of the challenging tasks for structural engineers is to mitigate the dynamic responses of a tall building structure subjected to wind loads in order to prevent human discomfort and motion sickness, and sometimes to enhance structural safety and integrity. Over the past decades, structural control methods have shown great potential to reduce the wind-excited vibration of tall building structures. The tuned mass damper (TMD) is one of the most widely used and accepted wind response control systems for tall buildings. Conventional passive TMD, which requires no external power, is reliable and does not destabilize the structure. However, the very narrow band of suppression frequency, the ineffective reduction of non-stationary vibrations, and the sensitivity problems due to mistuning are the inherent limitations of a conventional TMD [1,2]. In order to enhance the control performance of a TMD, an active force used to act between the structure and the TMD is introduced, that is an active TMD (ATMD) [3,4]. However, its stability problems, reliability and large power consumption are still major concerns to engineers. As a response to this, semi-active control devices are presented, which utilize the performance benefits while seeking to remedy the lack of stability of active systems. These devices only absorb or store the vibratory energy and they do not input the energy to the system. Therefore, they do not induce adverse effects on the stability of the system. Semi-active control systems, which can vary the stiffness and damping in real time, demonstrate better control effects than passive systems and consume less power than the active systems. Additionally, semi-active control devices can behave as passive devices in the event of a power loss, and are therefore more reliable [5–7]. Utilizing the performance benefits of semi-active control devices, the concept of a semi-active tuned mass damper (STMD) has been introduced in recent years. Hidaka et al. [8] conducted an experimental study of an STMD system coupled with a three-story building model under support ground motion. Pinkaew and Fujino [9] studied the control effectiveness of an STMD with variable damping under harmonic excitation. Varadarajan and Nagarajaiah [10] developed an STMD using a variable stiffness device and they have shown its effectiveness analytically and experimentally by using a small-scale three story structural model. Koo

* Corresponding author. Tel.: +82 53 810 2429; fax: +82 53 810 4625.
E-mail addresses: hskim72@sunmoon.ac.kr (H.-S. Kim), kangj@ynu.ac.kr (J.-W. Kang).

0141-0296/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engstruct.2012.03.038

et al. [11] presented an experimental robustness analysis of a semi-active tuned vibration absorber (TVA) subject to structural mass off-tuning using a magnetorheological (MR) damper.

One of the most promising semi-active devices is the MR damper. MR dampers are controllable fluid devices that employ MR fluids of which the rheological properties may be rapidly varied by an applied magnetic field. They can provide large force capacity, high stability, robustness and reliability. Furthermore, they are relatively inexpensive to manufacture and maintain and are insensitive to temperature so that they may be used for indoor and outdoor applications. Because of their mechanical simplicity, high dynamic range and low power requirements, they are considered to be good candidates for reducing structural vibrations and they have been studied by a number of researchers for seismic protection of civil structures [12–17].

Based on these background studies, a semi-active MR TMD (MR-STMD) is expected to be a promising control device for mitigating the wind-induced responses of a tall building structure. One of the challenges in the application of the MR-STMD is developing an appropriate control algorithm to determine the command voltage of the MR damper. Many control algorithms have been proposed to control the behavior of MR dampers or other semi-active devices. Skyhook and groundhook control policies [18,19], decentralized bang-bang control [20], the methods based on the Lyapunov theory [21], clipped-optimal control [22] and modulated homogeneous friction control [23] are some of the control algorithms used for semi-active control devices. Each of these control strategies has its own merits and limitations depending on the application and desired response. Also, note that the above-mentioned studies mainly focus on enhancement of the control performance of the semi-active control devices. However, in addition to the control performance, a constraint on the maximum allowable stroke of the MR-STMD is important for practical application and it must be considered in the design of the MR-STMD. To limit the stroke of the MR-STMD, overdamping or an additional damper may therefore be necessary, which results in a lower control efficiency of the MR-STMD, and thus in a larger response of the building structure. Since reduction of dynamic responses of the building structure is in conflict with reduction of the control device stroke, a multi-objective optimization approach is required in the design of semi-active control algorithms for the MR-STMD.

In this study, a multi-objective optimal semi-active control strategy for the response reduction of wind-excited tall buildings has been proposed. Because of the inherent robustness and ability to handle nonlinear systems and uncertainties, a fuzzy logic controller (FLC) is used in this study to operate an MR damper which is a key component of the MR-STMD. Although FLC has been used to control a number of structural systems, the selection of acceptable fuzzy membership functions has been subjective and time-consuming. To overcome this difficulty, a genetic algorithm (GA) is applied to the optimal design of FLC in this study. As mentioned above, because FLC should appropriately reduce both building structure and MR-STMD responses that are in conflict, a multi-objective optimization approach is introduced to the design of FLC. A multi-objective genetic algorithm is used to tune the membership functions and generate the rule base of a Mamdani type fuzzy controller [24].

In order to evaluate the performance of the proposed control method, a 76-story benchmark building subjected to wind excitation [25] is used as a numerical example structure. This benchmark building model is widely used by many researchers to verify control performance of control algorithms and devices [26,27]. The MR-STMD is installed on the top floor of the example building such as the passive TMD and ATMD presented in the benchmark problem. The benchmark problem specification [25] requires that the participants achieve the target control performance and to satisfy the control device capacity constraints simultaneously. To meet this requirement, a multi-objective optimization scheme that uses the Non-dominated Sorting Genetic Algorithm version II (NSGA-II) [28] is used in this study to determine the rule set of the FLC. NSGA-II has been demonstrated to be one of the most efficient algorithms for multi-objective optimization problems on a number of benchmarks. For comparative purposes, a sky–ground hook control algorithm is employed in numerical simulation for control of the MR-STMD. The effectiveness of the MR-STMD controlled by the control algorithm developed in this study is compared with that of the passive TMD and ATMD proposed in the benchmark problem [25]. Also, an investigation is carried out to determine whether the proposed control system can satisfy the design requirements and constraints provided in the benchmark problem.

2. Example building structure and performance evaluation criteria

2.1. 76-Story benchmark building model

The structural model used in this study is the benchmark building of a 76-story, 306-m tall concrete office tower proposed for the city of Melbourne, Australia [25]. The building has a square cross section with chamfers at two corners as shown in Fig. 1. This is a reinforced concrete building consisting of a concrete core and concrete frame. The core was designed to resist the majority of wind loads whereas the frame was designed to primarily carry the gravitational loads and part of the wind loads. The building is slender with a height to width ratio of 7.3. Therefore, it is wind sensitive. The total mass of the building, including the heavy machinery in the plant rooms, is 153,000 tons.

The 76-story tall building is modeled as a vertical cantilever beam (Bernoulli–Euler beam). A finite element model is constructed by considering the portion of the building between two adjacent floors as a classical beam element of uniform thickness, leading to 76 translational and 76 rotational degrees of freedom. Then, all the 76 rotational degrees of freedom have been removed by the static condensation. This results in a 76 degrees of freedom (DOF), representing the displacement of each floor in the lateral direction. This model, having (76×76) mass, damping, and stiffness matrices, is referred to as the "76 DOF model". The building with an ATMD is referred to as the "77 DOF model". The numerical computation of the controlled response quantities, including peak response, RMS response, etc., may be time consuming and computationally expensive for the 76 DOF and 77 DOF models. Hence the so-called state order reduction method has been used to derive

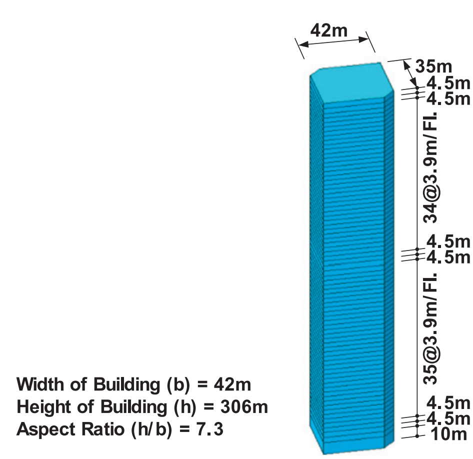

Fig. 1. 76-Story benchmark building model.