Expert Systems with Applications xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Expert Systems with Applications

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

Smart fuzzy control of reinforced concrete structures excited by collision-type forces

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A R T I C L E I N F O

Article history:
Available online xxxx

Keywords:
Fuzzy control
Smart control
Collision
High impact load
Magnetorheological (MR) damper
Proportional integral derivative controller (PID)
Smart structures

A B S T R A C T

The purpose of this study is to develop a smart controller for energy dissipation and damage mitigation of collision-excited reinforced concrete structures. This study is the first attempt to apply fuzzy logic theory to smart reinforced concrete structures equipped with MR dampers under collision forces for structural impact hazard mitigation. The parameters of the fuzzy controller are optimized using a backpropagation neural network. To train the fuzzy controller, a number of experiments were conducted using a smart reinforced concrete beam under a variety of impact loads. The smart reinforced concrete beam is equipped with a magnetorheological (MR) damper, accelerometers, linear variable differential transformer (LVDT), strain gages, and a voltage–current converter. It is implemented using National Instruments hardware with the LabView software. A proportional integral derivative controller (PID) is used as a baseline. It was shown from the comparisons of the fuzzy with the PID controllers that the smart fuzzy controller is an effective way to mitigate the complex impact response of reinforced concrete structures employing an MR damper.

1. Introduction

In recent years, there has been a growing interest in the impact behavior of reinforced concrete structures (Ahmadian & Norris, 2008; Arsava, Kim, & El-Korchi, 2015; Consolazio, Davidson, & Getter, 2010; Hongsheng & Suxiang, 2009; Ravindrarajah & Lyte, 2008; Wang & Li, 2006; Wiklo & Holnicki-Szulc, 2009a, 2009b). The high impact loads such as vehicle collisions, barge-bridge pier collisions, terrorist attacks, construction accidents, and gas explosions may cause structural collapse due to the intense dynamic stresses (Fig. 1). Thus, effective strategies for the response mitigation of structures under high impact loads should be developed to reduce the huge losses of both life and property.

1.1. Modern control

Smart control systems may be the key in absorbing and dissipating the external energy applied to structures (Arsava, Kim, & El-Korchi, 2013). In particular, magnetorheological (MR) dampers, which can be both operated as passive or active dampers, have received great attention for use in large-scale civil infrastructural systems (Mikułowski & Holnicki-Szulc, 2007; Spencer, Dyke, Sain, & Carlson, 1997). Fast response, reliable operation and low manufacturing cost are the most distinguishing features of the MR dampers (Dyke & Spencer, 1996; Dyke, Spencer, Sain, & Carlson, 1998; Dyke, Yi, Caicedo, & Carlson, 2001; Kim, Langari, & Hurlebaus, 2009, 2010; Yi, Dyke, Caicedo, & Carlson, 1999; Yi, Dyke, Frech, & Carlson, 1998). The MR dampers consist of a hydraulic cylinder filled with magnetic coils and MR fluids. The efficiency of the MR damper to absorb and dissipate the external energy can be optimized by changing the magnetic field applied over the MR fluid. Therefore, developing an effective control algorithm plays a key role in implementing the smart control technology in large structures.

Several control algorithms have been developed for use with the MR dampers in earthquake/wind engineering: Dyke, Spencer, Sain, and Carlson (1996a, 1996b) proposed clipped-optimal control to reduce dynamic response of structures under seismic loads. The control algorithm uses the acceleration feedback to adjust the voltage applied to the MR dampers. The effectiveness of the proposed algorithm was demonstrated on a 3-story smart building equipped with an MR damper. Dyke and Spencer (1997) compared the performance of a decentralized bang–bang controller, a Lyapunov controller, a clipped-optimal controller and a modulated homogeneous friction algorithm. It was shown from extensive simulations that the performance of the control system was highly dependent on the choice of algorithms employed. Ying, Ni, and Ko (2002) and Ni, Liu, and Ko (2002) applied the stochastic optimal control strategy to randomly excited nonlinear systems. Ni et al. (2002) studied

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http://dx.doi.org/10.1016/j.eswa.2015.05.024
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Fig. 1. High impact collision examples.

on the installation position of MR dampers. A 12-story building model and an 8-story building model subjected to seismic loads were investigated. It was demonstrated that the semi-active controller provides effective structural response reduction but the control efficiency is influenced by the location of MR dampers. Zhang and Roschke (1999) used a linear quadratic Gaussian with loop transfer recovery control to mitigate the acceleration response of tall structures under wind loads.

However, all the aforementioned controllers were designed based on the predefined parameters and require a full understanding of mechanics of structures (Zhao, Collins, & Dunlap, 2003). These controllers require the properties of structures (e.g., mass, damping and stiffness), and in some instances, even disturbances (magnitudes and frequencies). However, due to considerable uncertainty of the high impact loads and time-varying smart structures, it may be difficult to implement the aforementioned conventional controllers into the smart structures under high impact loads. On the other hand, to identify and control the given system model, the fuzzy logic algorithms use the input–output map of the structural system. Fuzzy logic algorithms use adaptive learning tools to increase the accuracy of the results. The only limitation of the fuzzy logic models is the requirement of extensive experimental studies to obtain input–output data sets for training the fuzzy model.

1.2. Intelligent control

Fuzzy logic-based controllers have attracted the attention of many investigators (Kim & Clark, 1999; Zhou & Chang, 2000). Liu, Gordaninejad, Evrensel, and Hitchcock (2001) proposed a closed-loop control system based on fuzzy logic to suppress the vibration of bridge decks under random excitations. It showed that the fuzzy control system significantly reduced the deck displacement, while the deck acceleration remained unchanged. Yeh, Chen, and Chen (2008) implemented a Takagi–Sugeno fuzzy model to parallel distribution compensation scheme to design a nonlinear fuzzy controller for the stabilization of time-delayed fuzzy systems. Numerical simulations were performed on a one-story building equipped with the tuned mass damper (TMD) subjected to the Taiwan Chi Chi earthquake. It was shown that the proposed controller was effective to decrease the deflection response of the structure excited by the earthquake. Chen (2009) developed a neural network (NN) approach, which combines the H^{∞} and Takagi–Sugeno fuzzy controllers, for use in structural systems equipped with tuned mass dampers. The objective of the proposed NN approach was to obtain a simple and practical control scheme for nonlinear structural systems under external resonant disturbances. A four-story frame structure was studied. A tuned mass damper system was designed according to the first frequency mode for reducing the state responses under a seismic excitation equivalent to the Taiwan Chi Chi earthquake. Numerical simulations demonstrated that the proposed method was able to stabilize the nonlinear structural system. Wilson and Abdullah (2005a) developed a fuzzy controller to regulate the damping properties of the structure-MR damper system under earthquake loads. They demonstrated that both floor displacement and acceleration responses were successfully reduced. However, tuning the fuzzy controllers was a difficult and sophisticated procedure due to a large number of parameters that define the membership functions and inference mechanisms (Wilson & Abdullah, 2005b). In this context, different approaches were also proposed such as genetic algorithms (GA) (Arslan & Kaya, 2001), neural networks (Chen, 2009; Lin & Lee, 1991), self-tuning (Maeda, Sato, & Murakami, 1990), gain scheduling (Jang & Gulley, 1994) and manual-tuning (Driankov, Hellendoorn, & Reinfrank, 1993).

One of the most recent researches has been performed by Kim (2014) on seismic response reduction of high-rise structures with fuzzy controlled MR-dampers. A 20-story building structure under artificial earthquake signals was investigated. Low damping elastomeric bearings and an MR damper were used to compose a smart top-story isolation system. A fuzzy logic controller was developed to control the MR damper and the parameters were optimized by multi-objective genetic algorithms. Based on numerical simulations, it was observed that the smart top-story isolation system can effectively reduce both the main structure and the isolated top story responses compared to the passive top-story isolation system. Another related work with our study was performed by Uz and Hadi (2014). An integrated fuzzy controller was proposed in order to provide the interactive relationships between damper forces and input voltages for MR dampers based on the modified Bouc–Wen model. The objective was to use MR dampers to prevent pounding damage and achieve a good seismic response mitigation of two adjacent structures. In the numerical study, adjacent 20-story and 10-story buildings subjected to the El Centro (1940) and the Kobe earthquakes were investigated. A total of 50 MR dampers were placed in the 10-story building and different current signals were studied. The proposed controller enhanced the seismic performance in terms of displacement responses and damper forces. Yang and Cai (2015) developed a fuzzy controller to reduce the excessive longitudinal vibration of a suspension bridge induced by vehicle braking forces and earthquake excitations. As a case study, Pingsheng Bridge in the Foshan city of Guangdong province in China was used. A three-dimensional finite element model of the bridge and eight MR dampers were constructed. Four dynamic loads including the vehicle braking forces, the Pingsheng Bridge earthquake wave, the El Centro wave, and the Takochi-oki wave and various control strategies (uncontrolled, passive and semi-active controllers with various voltages) were tested. It was

Please cite this article in press as: Arsava, K. S., et al. Smart fuzzy control of reinforced concrete structures excited by collision-type forces. *Expert Systems with Applications* (2015), http://dx.doi.org/10.1016/j.eswa.2015.05.024