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Editors

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Preface

The biennial CONTROLO conferences are the main events promoted by the Portuguese Association for Automatic Control—APCA, national member organization of the International Federation of Automatic Control—IFAC.

The CONTROLO 2016—12th Portuguese Conference on Automatic Control, Guimarães, Portugal, September 14–16, was organized by Algorithm, School of Engineering, University of Minho, in partnership with INESC TEC.

This edition of the conference has been approved for co-sponsorship by IFAC.

The conference had three partners: CEA—Comité Español de Automática, SPEE—the Portuguese Association for Education Engineering, and SPR—the Portuguese Association for Robotics.

We would like to thank the support of the Organizing Committee and the invaluable contributions of the Scientific Committee members, External Reviewers, Invited Speakers and Session Chairs. Last but not least, we want to thank the authors, for whom and by whom this event was made to happen.

We would also like to acknowledge EasyChair for their conference management system, which was freely used for managing the paper submission and evaluation process. Special thanks are due to the people in Springer.

Papers submitted to the conference were anonymously peer-reviewed by the Scientific Committee with a distribution operated by the EasyChair reviewer assignment algorithm. Based on the reviewers' ratings, 81 submissions were accepted conditionally to reviewers' recommendations being implemented.

A wide range of topics are covered by the 74 papers published in this volume cover. Of them 30, of a more theoretical nature, are distributed among the first five parts: Control Theory; Optimal and Predictive Control; Fuzzy, Neural and Genetic Control; Modeling and Identification; Sensing and Estimation.

Of a more applied nature, 44 papers are presented in the following eight parts: Robotics; Mechatronics; Manufacturing Systems and Scheduling; Vibration Control; Applications in Agricultural Systems; Power Systems Applications; General Applications; Education.

We believe that the papers in this volume, from cutting-edge theoretical research to innovative control applications, show expressively how automatic control can be used to increase the well-being of people.

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Brain Emotional Learning Based Control of a SDOF Structural System with a MR Damper

Manuel Braz César, José Gonçalves, João Coelho and Rui Carneiro de Barros

Abstract This paper describes the application of a Brain Emotional Learning (BEL) controller to improve the response of a SDOF structural system under an earthquake excitation using a magnetorheological (MR) damper. The main goal is to study the performance of a BEL based semi-active control system to generate the control signal for a MR damper. The proposed approach consists of a two controllers: a primary controller based on a BEL algorithm that determines the desired damping force from the system response and a secondary controller that modifies the input current to the MR damper to generate a reference damping force. A parametric model of the damper is used to predict the damping force based on the piston motion and also the current input. A Simulink model of the structural system is developed to analyze the effectiveness of the semi-active controller. Finally, the numerical results are presented and discussed.

Keywords Semi-active control · Brain Emotional Learning · MR damper

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1 Introduction

Over the last two decades many R&D projects have been devoted to develop vibration control systems for civil structures. Passive and active control systems are two well-known methodologies to mitigate wind and/or seismic-induced vibrations in slender and tall structures. In the last years, semi-active and hybrid control systems have been studied and proposed as a feasible alternative to traditional control approaches. Also, advanced controllers or soft computing techniques have been studied to take full advantage of these control systems.

In this regard, this study presents the application of a bio-inspired semi-active control system based on the brain limbic system of the human brain. A single-story, one-bay frame (SDOF system) with a MR damper located between the base and the top floor will be used to investigate the effectiveness of the proposed controller. In this case, the sensor and the actuator are placed in the same position and the control system has a collocated configuration. Initially, the uncontrolled response of the SDOF system the NS component of the El Centro earthquake loading was obtained, which is used as the reference response for the remaining numerical simulations. Then, passive and semi-active control modes are used to assess the efficiency of the proposed control strategy in reducing the response of the structural system. The modified Bouc-Wen model of a commercial MR damper (RD-1005-3 model) was used to represent the actuator in a passive configuration.

2 Brain Emotional Learning Controller

The Brain Emotional Learning (BEL) controller is a bio-inspired control algorithm based on the emotional learning mechanism of the brain limbic system, which has been employed to develop feedback controllers for complex control problems [1–4]. Basically, the BEL controller contains four main components: the amygdala (Am), the orbitofrontal cortex (OC), the sensory cortex (SC) and the thalamus (Th). The main control blocks of the BEL controller are illustrated in Fig. 1.

The amygdala and the orbitofrontal cortex are used to process the emotional signal (SE) while the sensory cortex and the thalamus receive and processes sensory inputs (SI). Sensory inputs (SI) are processed in the thalamus initiating the process of response to stimuli and passing those signals to the amygdala and the sensory

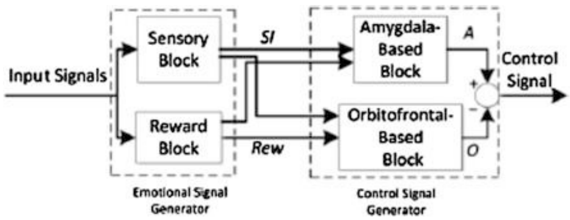

Fig. 1 Basic structure of Brain Emotional Learning controller [4]

cortex. Then, the sensory cortex operates by distributing the incoming signals properly be-tween the amygdala and the orbitofrontal cortex. In this controller, the learning procedure is mainly processed in the orbitofrontal cortex and is based on the difference between an expected punishment or reward and the received punishment or reward (Rew). The perceived punishment/reward (ES) is processed in the brain using learning mechanisms while the received punishment/reward represents an external input. If these signals are not identical, the orbitofrontal cortex inhibits and restrains the emotional response for further learning. Otherwise, the controller generates an output response [1, 2]. An important feature of this controller is its ability to gradually learn to deal with new situations and also the low computational requirements compared with other advanced controllers, which make the BEL controller particularly suitable to design real-time control and decision systems. Thus, the BEL controller presents significant advantages that can be exploited to design advanced control systems, particularly structural control systems for civil engineering applications. In what follows, a semi-active control system was developed based on this bio-inspired controller. A Simulink model of the proposed BEL controller is depicted in Fig. 2.

The principle of operation of the BEL controller can be summarized as follows: Sensory inputs (SI) enter through the thalamus, which has the task of initiating the process of a response to stimuli, and then pass those signals to the amygdala and the sensory cortex. The sensory cortex operates by distributing the incoming signals appropriately between the amygdala and the orbitofrontal cortex. The learning procedure is mainly processed in the orbitofrontal cortex and is based on the difference between an expected punishment/reward and the actual received punishment/reward (Rew). The perceived reward/punishment is developed in the brain using learning mechanisms while the received reward/punishment is an

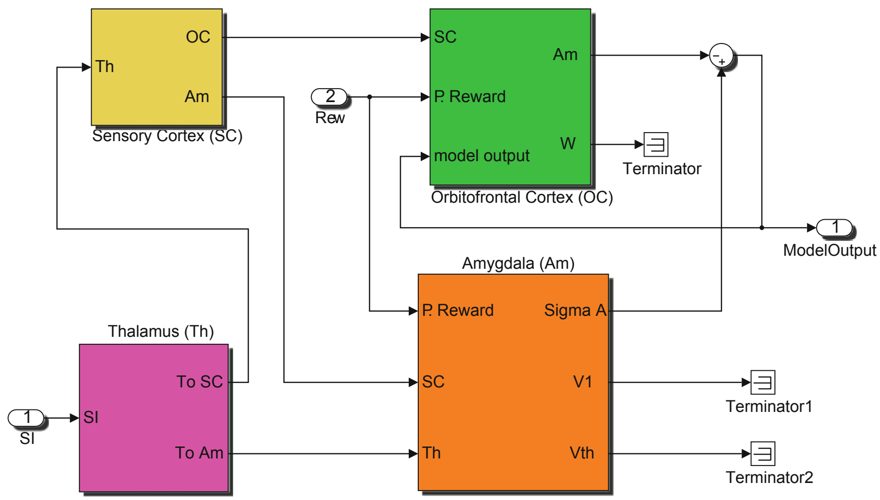

Fig. 2 Simulink model of the BEL controller

external input. If these signals are not identical, the orbitofrontal cortex inhibits and restrains the emotional response for further learning otherwise the controller produces a response output [1, 2].

The design procedure of a BEL based controller requires the definition of some model parameters to obtain the required control action. First, the sensory input signal should be adjusted before being forwarded to the sensory cortex. This modification is obtained using

$$A_i = G_{A,i} \cdot SI_i \tag{1}$$

$$OC_i = G_{OC,i} \cdot SI_i \tag{2}$$

where, $G_{A,i}$ and $G_{OC,}$i represent gains of the amygdala and the orbitofrontal cortex, respectively. Then, the amygdala and the orbitofrontal cortex learning processes occur through their internal weights update rule given by

$$\frac{dG_{Am,i}}{dt} = \alpha \cdot \mathrm{SI}_i \cdot \max\left(0, \mathrm{ES} - \sum \mathrm{A}_{m,i}\right) \tag{3}$$

$$\frac{dG_{OC,i}}{dt} = \beta \cdot \mathrm{SI}_i(\mathrm{MO} - \mathrm{ES}) \tag{4}$$

where α is the learning rate of Amygdala, β is the learning rate of orbitofrontal cortex, ES and MO are the emotional signal and the model output, respectively. The main drawback in designing this type of controller is mainly related with the appropriate definition of the emotional and the sensory signals so that they are able to approximately represent the state and the objective of the system and allowing the control system to achieve the best performance. Although there are several optimization procedures available for tuning these parameters, a common approach is to use a trial-and-error procedure.

3 Numerical Simulations

Consider the mass-spring-damper system excited by an earthquake loading as shown in Fig. 3. The SDOF system represents a scaled structure with the following properties: mass, m = 1000 kg; stiffness, k = 404,200 N/m and damping coefficient, ζ = 0.02.

In this case, the motion of the mass is defined by the absolute displacement $x_1(t)$ and consequently the relative displacement between the mass and the ground is given by $x(t) = x_1(t) - x_g(t)$, where $x_g(t)$ represent the absolute displacement of the ground. Thus, using a state space formulation, the equation of motion can be written as

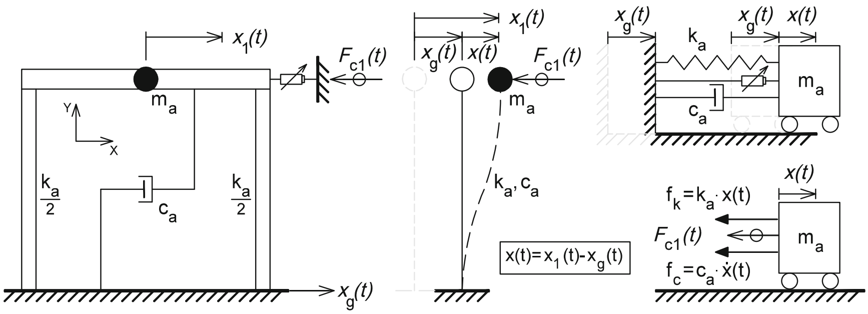

Fig. 3 SDOF system with a MR damper under earthquake excitation

$$z(t)=\begin{Bmatrix}\dot{x}(t)\\ \ddot{x}(t)\end{Bmatrix}=\begin{bmatrix}0 & 1\\ -k/m & -c/m\end{bmatrix}\begin{Bmatrix}x(t)\\ \dot{x}(t)\end{Bmatrix}+\begin{Bmatrix}0\\ -1/m\end{Bmatrix}f_c(t)+\begin{Bmatrix}0\\ -1\end{Bmatrix}\ddot{x}_g(t) \quad (5)$$

and response can be calculated using the state space output vector

$$y(t)=\begin{Bmatrix}x(t)\\ \dot{x}(t)\\ \ddot{x}(t)\end{Bmatrix}=\begin{bmatrix}1 & 0\\ 0 & 1\\ -k/m & -c/m\end{bmatrix}\begin{Bmatrix}x(t)\\ \dot{x}(t)\end{Bmatrix}+\begin{Bmatrix}0\\ 0\\ -1/m\end{Bmatrix}f_c(t)+\begin{Bmatrix}0\\ 0\\ -1\end{Bmatrix}\ddot{x}_g(t) \quad (6)$$

As can be seen, the system is being controlled by a generic actuator whose effect is defined by the control force $f_c(t)$ included into the equation of motion. In this case, the actuator is a MR damper that can be operated as a passive or semi-active device. In this type of smart damping devices, the viscosity of the MR fluid within the damper can be controlled depending on a prescribed input voltage or current. There are several numerical models to represent the hysteretic behavior of MR dampers. A common approach is to uses the modified Bouc-Wen model represented in Fig. 4 [5].

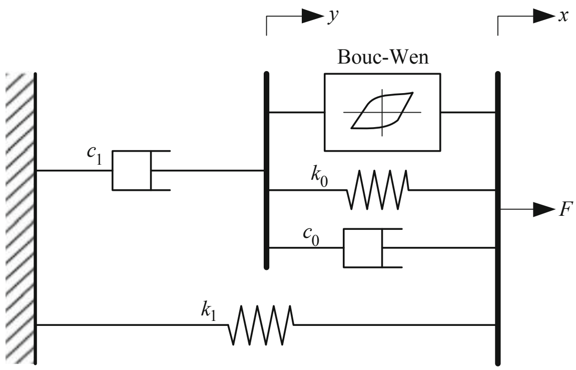

Fig. 4 Schematic representation of the modified Bouc-Wen model

The numerical formulation of this parametric and the corresponding model parameters are described by the following equations

$$F(t) = c_1\dot{y} + k_1(x - x_0) \tag{7}$$

$$\dot{y} = \frac{1}{c_0 + c_1}[\alpha z + c_0\dot{x} + k_0(x - y)] \tag{8}$$

$$\dot{z}(t) = -\beta|\dot{x}(t)|z(t)|z(t)|^{n-1} - \gamma\dot{x}(t)|z(t)|^n + A\dot{x}(t) \tag{9}$$

The model parameters are defined based on experimental tests and some parameters are current (or voltage) independent, i.e., their values are not significantly affected by the magnetic field applied to the MR fluid. A commercial MR damper (RD-1005-3 by Lord Corp., USA) was experientially tested to obtain the model parameters [6]. In this case, the current/voltage independent parameters are $A = 10.013$, $\beta = 3.044\ \text{mm}^{-1}$, $\gamma = 0.103\ \text{mm}^{-1}$, $k_0 = 1.121$ N/mm, $f_0 = 40$ N and $n = 2$. The remaining parameters are current dependent and can be defined by the following polynomial expressions

$$\alpha(I) = -826.67I^3 + 905.14I^2 + 412.52I + 38.24 \tag{10}$$

$$c_0(I) = -11.73I^3 + 10.51I^2 + 11.02I + 0.59 \tag{11}$$

$$c_1(I) = -54.40I^3 + 57.03I^2 + 64.57I + 4.73 \tag{12}$$

A first-order time lag involved in the current driver/electromagnet during a step command signal is also included in the numerical model of the device, which in this case is defined by a first order filter ($\eta = 130\ \text{s}^{-1}$).

The SDOF system will be now subjected to the 1940 N-S component of the El-Centro earthquake time history (peak acceleration of 3.42 m/s^2). Since the current SDOF system represents a scaled structure, the earthquake signal needs to be decreased to represent the magnitude of displacements that would be observed in experiments tests. In this particular case, the time was scaled to 50 % of the full-scale earthquake time history as shown in Fig. 5.

It is important to notice that MR dampers are semi-active devices in the sense that they are passive actuators with adjustable properties. Also, they cannot be directly controlled to generate a specific damper force because the damper response is dependent on the local motion of the structure where the device is located. A practical approach to control the MR damper is to adjust the voltage applied to the current driver to increase or decrease the damper force [7]. A Simulink model of the proposed semi-active BEL controller was developed as shown in Fig. 6.

The BEL block represents the primary controller that computes the required control action and the clipping block is a secondary control unit that adjusts the desired damping force to the MR damper control signal (operating current). The Simulink model of the BEL controller is shown in Fig. 7.

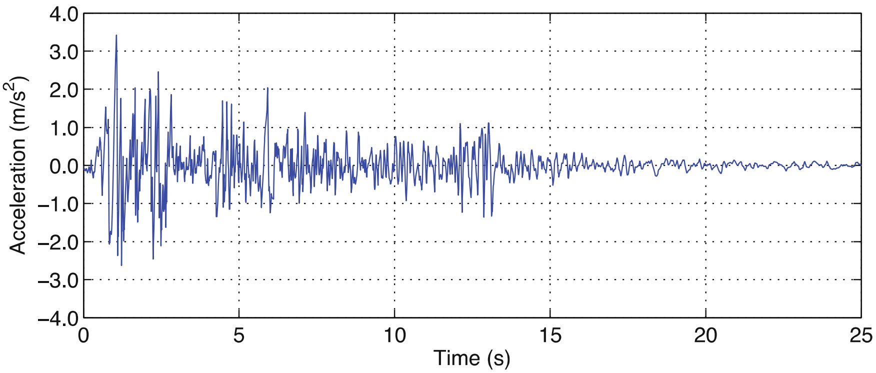

Fig. 5 Time-scaled N-S component of El-Centro earthquake ground motion

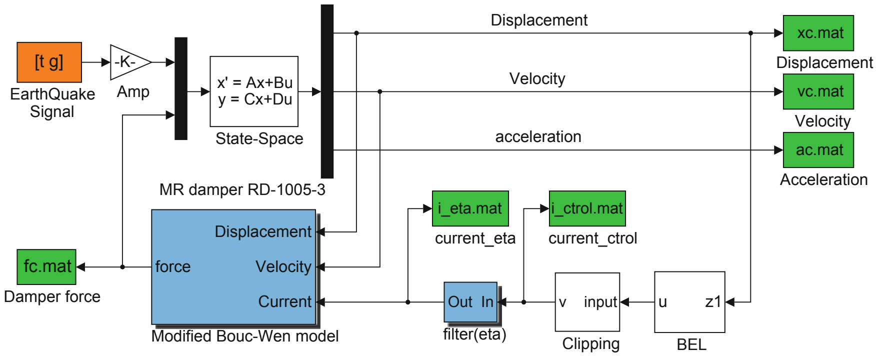

Fig. 6 Simulink model of the BEL control system

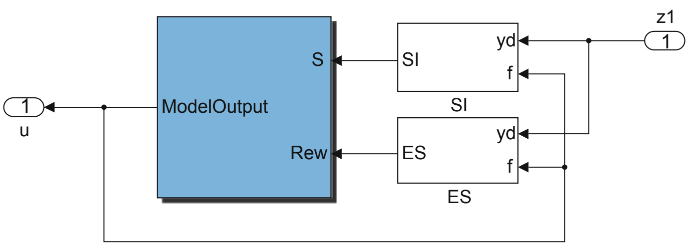

Fig. 7 Simulink model of the BEL controller for the SDOF system

In this case the sensory input (SI) and the emotional signal (ES) can be related with the system response y_d and the BEL model output u, which are determined by

$$SI = w_1 y_d + w_2 u \tag{13}$$

$$ES = w_3 y_d + w_4 \int u\, dt \tag{14}$$

where wi are weight factors that define the relative importance given to the drift response ($z_1 = y_d$) and the output of the BEL controller (f = u). The sensory and emotional outputs are forwarded as the stimuli and the reward/punishment for the BEL controller, respectively. Finally, the BEL control block uses this information to construct a response (model output) that represents the control action. The learning rates (α and β) represent model parameters that must be adjusted in accordance with the input variables to achieve the required control action. The main drawback of the BEL controller is related essentially with the appropriate definition of emotional and sensory signals that are able to represent with sufficient precision the system state and the control objective in order to maximize the performance of the control system. In this study, the learning rates for the amygdala and orbito-frontal cortex are defined as $\alpha = 1$ and $\beta = 1$, respectively. The sensory and the emotional outputs are determined by applying weight factors $w_1 = 2$, $w_2 = 1$, $w_3 = 2$ and $w_4 = 1$, which provide the best results for the SDOF system under control and were found after a trial-and-error procedure.

4 Results

The MR damper will be used in both passive and semi-active configurations, i.e., with a constant operating current during the numerical analysis and in a controllable mode in which the semi-active BEL controller is used to determine the control action.

Two passive configurations are used: Passive OFF, a passive control mode in which the MR damper is operating with zero input current (i.e., I = 0.00 A) and Passive ON, a passive configuration in which the MR damper has a constant current I = 0.50 A (selected as the maximum operating level).

The time responses obtained with the BEL control algorithm along with the uncontrolled responses are displayed in Fig. 8. In general terms, the results demonstrate that the BEL controller is effective in commanding the MR damper allowing a significant reduction of the structural response.

The damper force and the corresponding control signal times histories obtained with the BEL controller are presented in Fig. 9. As can be observed in the Simulink model of the control system, a clipping unit is responsible to change the controller output to a bi-state control output (minimum and maximum operating current) compatible with the semi-active control operation of the MR damper. This principle

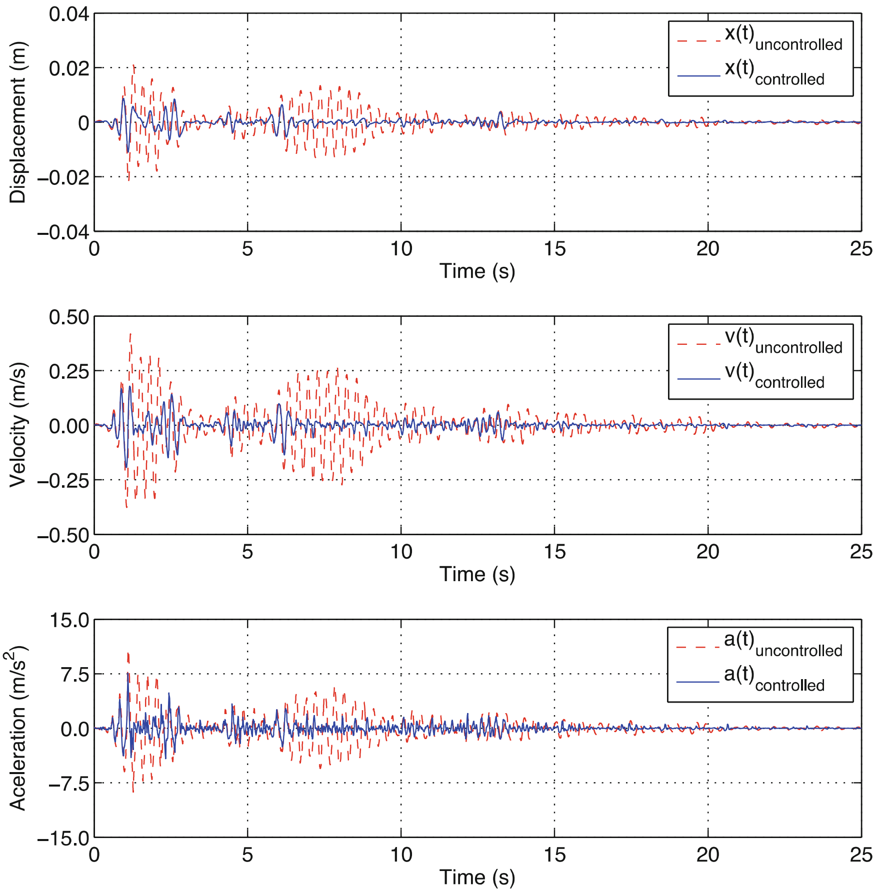

Fig. 8 Structural response obtained with the semi-active BEL controller

is analogous to that used in other clipped based controllers and therefore the present control strategy can be classified as a clipped-BEL controller.

The evaluation criteria are based on a comparison of the peak responses of the controlled system to those of the uncontrolled system, passive OFF and ON cases. The results of achieved with this analysis are summarized in Table 1.

Regarding the passive control mode, it can be seen that the passive OFF configuration has almost no effect in the system response, especially in reducing the peak acceleration (around 3 %). The passive ON mode has a major effect in the system response that results in peak responses being significantly reduced (around 60 % in peak displacement/velocity and 40 % in peak acceleration). The clipped-BEL controller presents a significant improvement over the passive OFF case but is not as effective as the passive ON case. This is related with the weighting parameters used in this study.

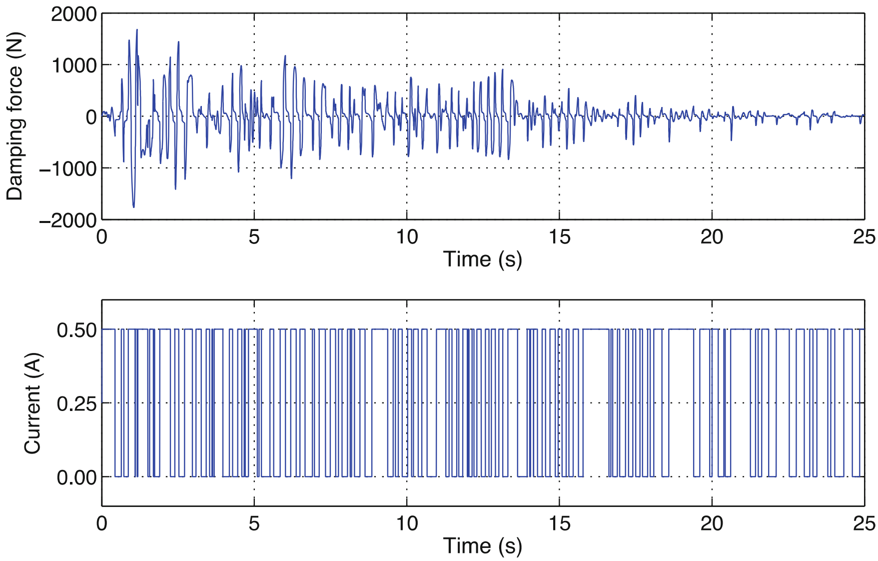

Fig. 9 Damper force and corresponding operating current (BEL controller)

Table 1 Peak responses under the time-scaled El-Centro earthquake

Control strategy		x (m)	$\dot{x}$ (m/s)	$\ddot{x}$ (m/s^2)	f (N)
Uncontrolled		0.0221 (1.00)	0.4184 (1.00)	10.761 (1.00)	–
Passive OFF	Modified Bouc-Wen	0.0203 (0.09)	0.3859 (0.08)	10.475 (0.03)	261.5
Passive ON	Modified Bouc-Wen	0.0093 (0.59)	0.1573 (0.62)	6.8376 (0.36)	1542.9
Clipped-BEL		0.0110 (0.50)	0.1934 (0.54)	7.5481 (0.30)	1768.1

Note values under parenthesis represent the percentage of response reduction

As already stated, the main drawback regarding the implementation of the BEL based control system is related with the optimization of the controller parameters. The selection of appropriate weight factors is decisive to obtain the best performance of the BEL controller. This can be done by using an optimization technique (e.g., genetic algorithms) instead of the trial-and-error procedure used in this case. Nevertheless, it was verified that the proposed BEL controller can be implemented in structural control systems with MR dampers, although further research is required to improve the performance of the proposed controller in order to take advantage of the properties of this type of controllable devices. It is also important to mention that this is a SDOF structure with a collocated control system (variable damping system) and therefore the outcome of the variable damping system is not as effective or visible as for multi-DOFs structural systems.

5 Conclusions

A Brain Emotional Learning based semi-active control system was implemented to reduce the response of a SDOF structure. It was verified that the BEL controller was able to reduce the system response compared with the uncontrolled case and the passive OFF control mode. However, the performance of the proposed controller was not as good as using the MR damper in a passive ON mode. This poor performance is mainly related with a weak weighting parameter optimization procedure. Despite that, this study has proven the potential of the BEL algorithm to develop semi-active control system for structural applications. The main advantage of the proposed BEL controller is that only the drift response of the structure is required to determine the control action, i.e., in this SDOF structural system only the floor displacement need to be measured. This can be a significant advantage for multi-DOFs systems.

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