A SURVEY OF SEMI-ACTIVE CONTROL WITH MR DAMPERS

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Abstract

The present work describes part of the R&D on using a semi-active structural control technique in a civil engineering experimental model frame equipped with a MR damper, developed within COVICOCEPAD project approved in the framework of Eurocores program S3T. Some results are provided associated with the calibration of a magneto-rheological (MR) damper at FEUP (Faculdade de Engenharia da Universidade do Porto) as well as on the experimental modal identification of the dynamic properties of a small-scale metallic frame, with and without the inclusion of a specific MR device. Some numerical results of the controlled frame under simulated earthquakes are given, to be later compared with the experimental results of such frame installed in a Quanser shaking table.

Keywords: Response control, Clipped optimal control, MR dampers, Semi-active control.

1. INTRODUCTION

In the last two decades R&D of structural vibration control devices for buildings and bridges has been intensified in order to answer the construction market needs that demand more effective systems to reduce the damage caused on structures by seismic and wind loadings. Although the main purpose of a seismic design is to protect the population from the consequences of a severe earthquake, the protection of the building stock may also be regarded as an important option during the conception and design process.

In this paper is addressed some on-going R&D on the vibration control of a three degree-of-freedom (3-DOF) scaled metallic frame with a MR damper [1, 2].

A MR device was tested in the laboratory to obtain the main rheological characteristics in order to develop a numerical model to simulate its behavior. Then a 3-DOF scaled frame was assembled and system identification techniques using an impact hammer procedure were performed to obtain the experimental dynamic properties of this structural system. Based on these results a numerical model was created to initiate the semi-active control research process in order to investigate and calibrate the frame behavior with the MR damper.

2. SEMI-ACTIVE CONTROL OF MR DAMPERS

The MR damper performance is often characterized by using the force versus velocity relationship. MR dampers have the possibility to change the damping characteristics based on a force versus velocity envelope, which can be described as an area rather than a line in the force-velocity plane.

Many authors have developed modeling techniques for the MR dampers. The Bouc-Wen model shown in Fig. 1 allows modeling nonlinear hysteretic systems and is frequently used to model MR dampers [3].
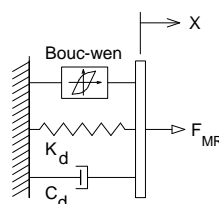

Figure 1: Bouc-Wen model for a MR damper.

The MR force of the device can be computed by

$$F_{MR} = c_0 + k_0(X - X_0) + \alpha z$$
(1)

In this equation FMR is the predicted damping force, k0 is the accumulator stiffness, c0 is the viscous damping and z is the evolutionary variable of the first order nonlinear differential equation

$$\dot{z} = -\gamma |\dot{x}| z |z|^{n-1} - \beta \dot{x} |z|^n + A\dot{x}$$
(2)

The parameters β, γ and A allow controlling the linearity in the unloading and the smoothness of the transition from the pre-yield to the post-yield region.

The equation of motion that describes the behavior of a controlled building under an earthquake load [4] is given by:

$$M\ddot{x} + C\dot{x} + Kx = -\Gamma f - M\lambda \ddot{x}_g$$
(3)

where M is the mass matrix, C is the damping matrix, K is the stiffness matrix, x is the vector of floors displacements, $\dot{X}$ and $\ddot{X}$ are the floor velocity and acceleration vectors respectively, f is the measured control force, λ is a vector of ones and Γ is a vector that accounts for the position of the MR damper in the structure. This equation can be rewritten in the state-space form as

$$\begin{cases} \dot{z} = Az + Bf + E\ddot{x}_g \\ y = Cz + Df + v \end{cases}$$
(4)

where z is the state vector, y is the vector of measured outputs and v is the measurement noise vector. The other matrix quantities are defined by

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ M^{-1}\Gamma \end{bmatrix} \quad E = -\begin{bmatrix} 0 \\ \lambda \end{bmatrix}$$

$$C = \begin{bmatrix} -M^{-1}K & -M^{-1}C \\ I & 0 \end{bmatrix} \quad D = \begin{bmatrix} M^{-1}\Gamma \\ 0 \end{bmatrix}$$
(5)

To perform the numerical analysis a single bay three-storey frame (three degree of freedom in shear frame configuration) was designed (Fig. 2). The columns at the corners, having the same stiffness, are made of aluminum with an average cross section of 1.5mm by 50mm and the diaphragm floors are made of polycarbonate plates monolithically attached to the columns. The frame mass is around 19 kg and each floor has an average mass of 3.65 kg. The stiffness of the experimental frame was designed to keep the fundamental frequency near to 2 Hz.

Figure 2: Metallic scaled frame at the shaking table.

Assuming a three storey shear frame, the frame mass (M) and the stiffness matrix (K) are obtained as:

$$M = \begin{vmatrix} 3.65 & 0 & 0 \\ 0 & 3.65 & 0 \\ 0 & 0 & 3.65 \end{vmatrix} (kg)$$

(6)

$$K = \begin{vmatrix} 5820 & -2910 & 0 \\ -2910 & 5820 & -2910 \\ 0 & -2910 & 2910 \end{vmatrix} (N/m)$$

(7)

The three natural frequencies obtained with the above mass and stiffness matrices are: 2.00Hz, 5.60Hz and 8.09Hz. A damping of 0.5% along with the above mass and stiffness matrices formed the initial parameters for the modal analysis.

After calibrating the MR damper numerical model it is necessary to select a proper control algorithm to efficiently use this device in reducing the dynamic response of structural systems. The fundamental condition to operate the MR damper is based on a generated damping force that is related with the input voltage; the control strategy is selected so that the damping force can track a desired command damping force.

In the last few years several approaches have been proposed for better selection of the input voltage that must be applied to the MR damper to achieve the maximum performance [5-7]. In the present numerical study a Clipped Optimal control will be used as shown in Fig. 3.
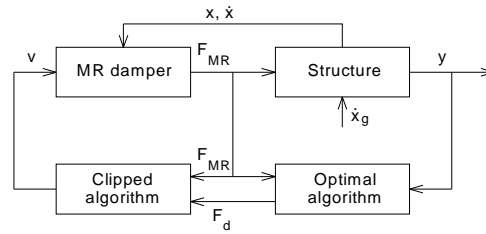

Figure 3: Clipped Optimal controller.

This strategy consists of a Bang-Bang (on-off) controller that causes the damper to generate a desirable control force that is determined by an "ideal" active controller (in state feedback form). A force feedback is used to produce the desired control force fd, which is determined by a linear optimal controller Kk(s), based on the measured structural responses y and the measured damper force fc.

Only applied voltage va can be commanded (and not the damper force) that is selected by va= vmax H (fd - fc) fc in which vmax is the voltage level associated with the saturation of the magnetic field in the MR damper and H(.) is the Heaviside step operator.

The following voltage selection algorithm is applied: When the actual force being generated by the damper fc equals the desirable force fd, the voltage applied remains the same. When the magnitude of the force fc is smaller than the magnitude of fd and both forces have the same sign, then the voltage applied is set to its maximum level to increase the damper force. Otherwise, voltage is set to zero.

The selected optimal controller is based on a Linear Quadratic Optimal Control. In this numerical study the linear controller is obtained with a Linear Quadratic Regulator (LQR) strategy that will be used in a state feedback control.

The main objective to design the optimal controller is to obtain an optimal control vector fc(t) that minimizes a performance index J. In this case a quadratic performance index in z(t) and fc(t) is used and represented by:

$$J = \int_0^{t_f} \left[z^T(t) \cdot Q \cdot (t) + f(t) \cdot R \cdot f(t) \right] dt$$

(8)

In eq. 8 Q and R are weighting matrices associated with the state variables and with the input variables respectively. The magnitudes of these matrices are defined according to the importance that is given to the state variables and the control forces on the minimization process. Increasing the values of Q matrix elements implies the prioritization of the response reduction over the control forces.

On other hand, increasing the values of the elements of R implies the prioritization of the control forces over the response reduction.

The solution of the LQR problem is based on the analysis of the algebraic Riccati equation

$$PA + A^T P - PBR^{-1}B^T P + Q = 0$$

(9)

3

and the LQR problem can be solved using a linear state feedback with a constant gain G according to

$$u(t) = -G \cdot x(t) = \left[R^{-1} B^T P \right] \cdot x(t)$$

(10)

To select the appropriate values for Q and R the following procedure was used in this study: it was assumed that R matrix has the following form

$$R = r \cdot I$$

(11)

where I is the identity matrix and r is a multiplier, and that Q matrix assumes the following form

$$Q = \begin{bmatrix} K & 0 \\ 0 & 0 \end{bmatrix}$$

(12)

A parametric study was carried out by changing the value of the multiplier (10-1, 10-3, 10-5, 10-7, 10-9, 10-11, 10-13 and 10-15) and then verifying the efficiency of (reduction of floor displacements, accelerations and also the control force on the actuator). It was verified that decreasing this value implies a more marked reduction of the response.

In this case a significant reduction (up to 90% of the floor displacements and accelerations) was obtained with r=10-9.

3. EXPERIMENTAL SETUP

According to the scheduled research program [8], the next stage was related to the study of the experimental dynamic behavior of a 3DOF scaled metallic load frame equipped with a semi-active device. The experimental frame located at FEUP-Covicocepad Lab, can be forced dynamically using the Quanser shaking table II as the dynamic loading actuator.

To study the semi-active control strategy a small MR damper shown in Fig. 4 was placed at the first floor level attached to the frame and rigidly attached to the shaking table. To measure the damping force values generated during the experimental tests a load cell was placed in the MR damper support system.

Figure 4: RD-1097-01 MR Damper.

The parameters of the MR damper shown in Fig. 5 are: minimum force in passive-off mode < 9 N (for current 0.0A at piston velocity 200 mm/s), maximum force 100 N (for current 1.0A and piston velocity 51 mm/s), stroke ±25 and response time < 25 ms (time required to reach 90% of the steady-state value of force under a step change of the current from 0.0 to 1.0A, for 51 mm/s).

3.1 EXPERIMENTAL MR DAMPER BEHAVIOR

To study the behavior of a MR damper some experiments were carried out on a MTS universal testing machine (Mechanical Engineering Laboratory at FEUP) with two MR dampers: RD-1005-03 and RD-1097-01 supplied by LORD Corporation.

After assemblage the MR dampers were forced with a sinusoidal signal at a fixed frequency, amplitude and current supply. To obtain the response under several combinations of frequencies, amplitudes and current supplies a series of tests were carried out.

The RD-1097-01 MR damper was the selected device to be used in this analysis due to the small range of forces involved in the scaled frame dynamic analysis. In order to use the Bouc-Wen model, the following current (I) dependent parameters were used:

$$\begin{cases} \alpha(I) = 72.80 I^3 - 42.88 I^2 + 14.83 I + 0.29 \\ c_d(I) = -9.37 I^4 + 10.22 I^3 - 4.33 I^2 + 0.89 I + 0.02 \end{cases}$$

(13)

And the current independent parameters are: k0= 0.0, β= -7.078, γ=10.614, A=36.21 and n= 1.0. These are approximate values that probed to capture very well the hysteretic behaviour of the MR damper [9].

3.2 SYSTEM IDENTIFICATION

An impulse hammer test was carried out in order to obtain the modal parameters of the structure. The structural response was measured with a piezoelectric accelerometer (Bruel & Kjaer type 4393 with measuring amplifier type 2525) placed at the first floor and a portable real-time analyzer (OROS 35 real-time multi-analyzer) that was used to perform the necessary mathematical rationing on input and response signals to produce the desired transfer function.
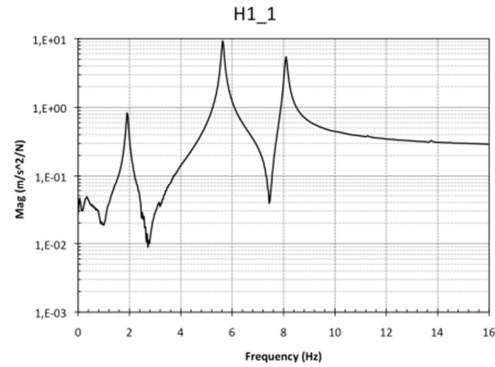

Figure 6: Frequency Response Function of H1_1.
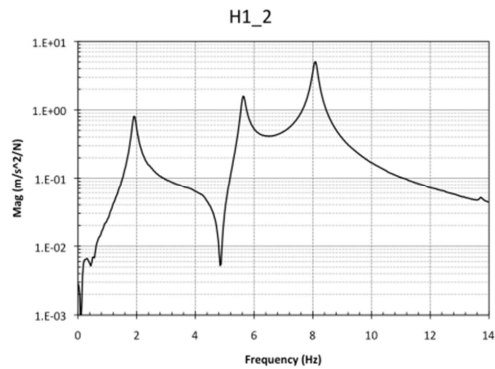
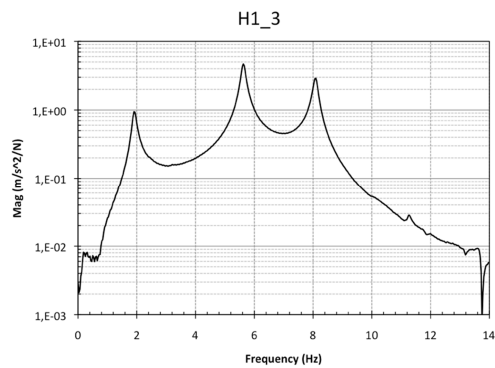**Figure 7: Frequency Response Function of H1_2.**

Figure 8: Frequency Response Function of H1_3.

The desired frequency response functions (magnitude) for each input/output measurements are shown in Figs. 6-8.
The parameters of the scaled frame were then obtained based on the data provided by these functions and are tabulated in Table 1.

Table 1: Parameters of the scaled frame.

Frequency	Damping	Modal Participation
1,913986 (1st mode)	0.03157	34.43248
5,627778 (2nd mode)	0.01198	35.25975
8,086245 (3rd mode)	0.00899	30.30777

4. RESULTS

To study the response of the structure with the semi-active controller, a few characteristic earthquake records were considered; those will be also input in the Quanser shaking table of FEUP-Covicocepad laboratorial facilities, in order to experimentally calibrate and numerically compare different control strategies. The results considered herein are just for the El Centro earthquake record selected as input.

The three horizontal floor displacements were selected as the parameters (output) to verify the efficiency of the control law. Some results of this numerical analysis are plotted in Figs. 11-14 for uncontrolled and semi-active controlled scenarios.
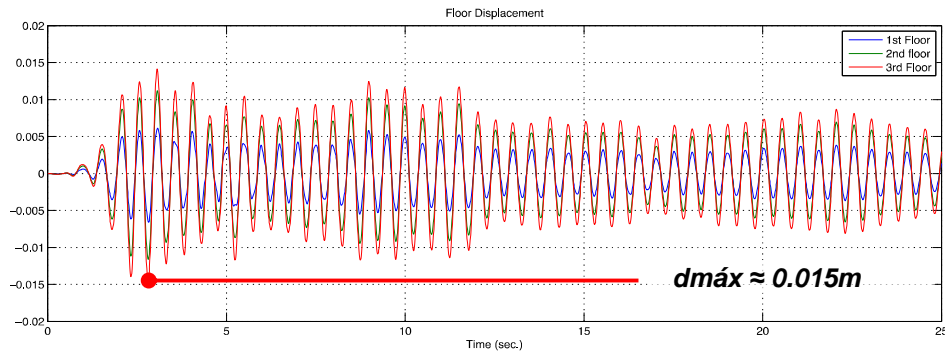
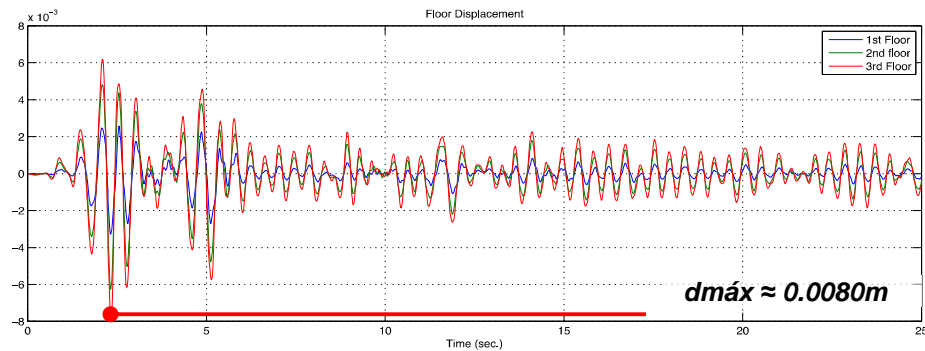

Figure 9: Uncontrolled response without MR damper.

Figure 10: Uncontrolled response with MR damper @ 0.00A.

The structure response plot shown in Fig. 9 was obtained without any device connected to the scaled frame (non-controlled response). Then, the MR damper was attached to the 1st floor in a passive configuration (without current applied) and a new displacement response plot was obtained as shown in Fig. 10. It is clear that a significant displacement reduction is obtained even with the MR damper in passive mode.
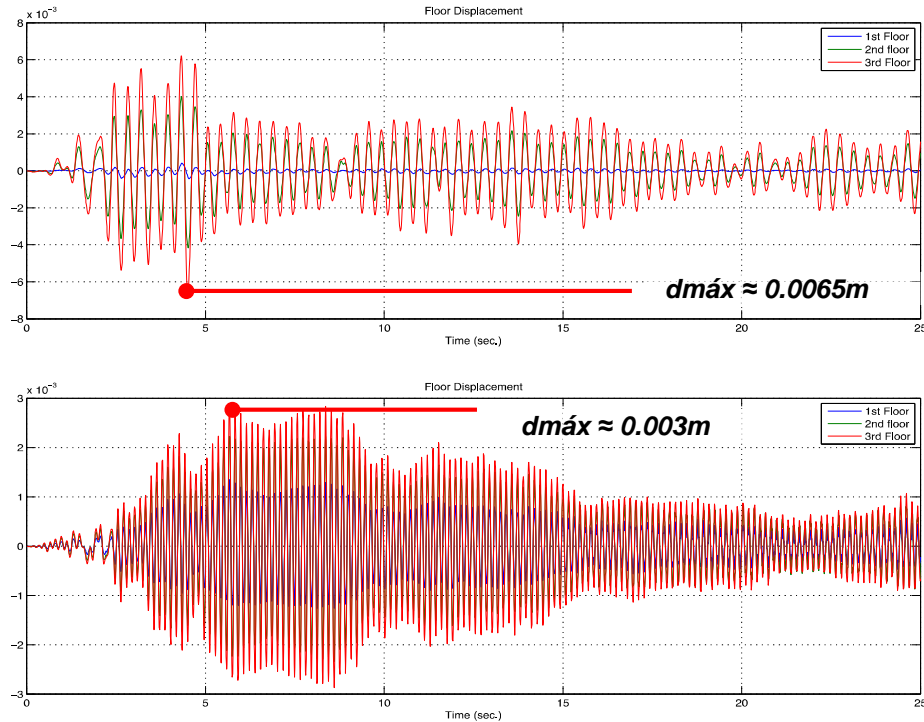
Figure 12: Semi-active control response.

A new analysis was carried out with the MR damper acting as a passive device but with a constant current of 0.25A. As it can be verified in Fig. 11, the three floor displacements were considerably reduced (from 0.008 to 0.006 m) due to the increase of damping and stiffness at this level. This means that the MR damper introduces a partial constraint and as consequence the frame behaves like a 2 DOF system above the first floor level. Finally, the semi-active controller was activated and the horizontal floor displacements were again plotted as shown in Fig. 12.

As expected, the semi-active control based on the Clipped Optimal algorithm was successfully applied. The lateral displacements of the building floors were reduced significantly during the earthquake duration, as visible by the maximum displacement of the top floor reaching a value of about 0.003 m. This value corresponds to 20% of what was reached initially without control; and to 40% of what was reached with passive control.

Although the main objective of this analysis is to validate the efficiency of the Clipped Optimal algorithm, it is clear that further numerical and experimental research must be carried out. Since this is an ongoing research program, the next step will be the implementation of new control strategies.

5. CONCLUSIONS

This paper addresses the vibration control of a 3-DOF experimental metallic frame with a MR damper. The MR damper was tested to find the dynamic properties and a numerical model was developed to simulate its behaviour. System identification allowed obtaining the dynamic response of this structural system. In a numerical example the three-story structure was controlled using a MR damper on the first floor. The simulated results show that the Clipped Control algorithm resulted in an improvement over the uncontrolled system.

6. ACKNOWLEGMENTS

7. REFERENCES

1. M. Cesar, R. Barros. (2010) Semi-Active Control of a Metallic Scalled Frame with a MR Damper: Numerical and Experimental Research. in School and Symposium on Smart Structural System Technologies (S3T-2010), Editors: R. Barros and A. Preumont, pp. 419-440. Faculty of Engineering of the University of Porto (FEUP), Porto, Portugal.

2. R. Barros, A. Baratta, O. Corbi, M. Cesar, M. Paredes.(2009) Some Research on Control of Vibrations in Civil Engineering under COVICOCEPAD Project, in Proceedings of the Third International Conference on Integrity Reliability & Failure (IRF 2009), Editors: J.F. Silva Gomes and Shaker A. Meguid, Ref: S2606-A0583, Edicoes INEGI, Portugal.

3. S. Dyke, B. Spencer, M. Sain , J. Carlson.(1996) Modeling and Control of Magneto-Rheological Dampers for Seismic Response Reduction, Smart Materials and Structures, Vol. 5, pp. 565-575.

4. V. Gattulli, M. Lepidi, F. Potenza.(2010) Mitigation of Seismic Vibration by Semi-Active Control, in School and Symposium on Smart Structural System Technologies (S3T-2010), Editors: R. Barros and A. Preumont, pp. 347-367. Faculty of Engineering of the University of Porto (FEUP), Porto, Portugal,

5. S. Dyke, B. Spencer Jr.(1997) A Comparison of Semi-Active Control Strategies for the MR Damper, in Proceedings of the IASTED International Conference, Intelligent Information Systems, The Bahamas.

6. L. Jansen, S. Dyke.(1999) Semi-active control strategies for MR dampers: a comparative study. ASCE Journal of Engineering Mechanics, Vol. 126, No. 8, pp. 795-803.

7. C. Oliveira, R. Bairrão, R. Barros, L. Guerreiro(2008) The New Generation of Seismic Semi-Active and Active Protection Systems, in Proceedings of the 4th European Conference on Structural Control (4ECSC), Paper 227, Russia.

8. R. Barros.(2008) Project COVICOCEPAD under Smart Structural Systems Technologies of Program Eurocores, in Smart Materials and Smart Structures Technology, Editors: B.F. Spencer, M. Tomizuka, C.B. Yun, W.M. Chen, R.W. Chen, London: Taylor & Francis Group.

9. Y. Shen, M. Golnaraghi, G. Heppler.(2007) Load-Leving suspension system with a magnetorheological damper, Vehicle System Dynamics, 45:4, 297-312.