Semi-active Vibration Control of Buildings using MR Dampers: Numerical and Experimental Verification.

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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 MR damper at FEUP as well as on the experimental modal identification of the dynamic properties of a small-scale metallic frame, without and with 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: Semi-active Control, Control of Vibrations for Smart Structures, Semi-Active Devices

1. INTRODUCTION

Seismic isolation and passive energy dissipation are two well-established techniques validated by a huge amount of real applications (Naeim and Kelly, 1999; Cesar and Barros, 2007). Magneto-rheological fluid based devices have the appropriate features justifying the relevance of these for possible civil engineering applications and therefore the attention of researchers to study its potential as vibration control hardware (Dyke *et al*., 1996 ; Gatulli *et al*., 2010). The control strategy for these devices is based on semi-active control that may be more reliable and stable than active control.

In the last two decades R&D of structural vibration control devices for buildings and bridges has been intensified to reply to construction market needs that demand more effective systems to decrease the damage caused on structures by seismic and wind loading. Although the main purpose of a seismic design is to protect the population from the consequences of a severe earthquake, the protection of investment 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 3-DOF scaled metallic frame with a MR damper (Cesar and Barros, 2010). An equivalent device was tested in the laboratory to obtain the main rheological characteristics in order to develop a numerical model to simulate its behaviour. 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 behaviour with the MR damper.

2. SEMI-ACTIVE CONTROL OF STRUCTURES WITH MR DAMPERS

MR fluids have become an extensively studied “smart” fluid and some experimental research has been done in the last years to produce a “smart” control device. The MR damper performance is often characterized by using the force vs. velocity relationship. MR dampers have the possibility to change the damping characteristics leads to a force vs. velocity envelope that can be described as an area rather than a line in the force-velocity plane.

Many authors have developed modelling techniques for the MR dampers. The Bouc-Wen model shown in Fig. 2.1 allows modeling nonlinear hysteretic systems and is frequently used to model MR dampers (Dyke *et al*., 1996).

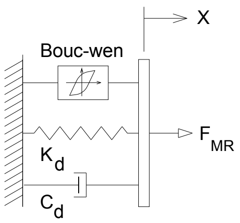


Figure 2.1. Bouc-Wen model for a MR damper

According with the Bouc-Wen model shown in Fig. 2.1, the MR force can be computed by

$$F_{MR} = c_0 + k_0\left(x - x_0\right) + \alpha z \tag{2.1}$$

In this equation F_{MR} is the predicted damping force, k_0 is the accumulator stiffness, c_0 is the viscous damping and z is the evolutionary variable of the first order nonlinear differential equation

$$\dot{z} = -\gamma\left|\dot{x}\right| z\left|z\right|^{n-1} - \beta\dot{x}\left|z\right|^{n} + A\dot{x} \tag{2.2}$$

The parameters β, γ and A allows 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 behaviour of a controlled building under an earthquake load, Barros *et al*. (2009), is given by:

$$M\ddot{x} + C\dot{x} + Kx = -\Gamma f - M\lambda\ddot{x}_g \tag{2.3}$$

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 the 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

$$\begin{aligned} \dot{z} &= Az + Bf + E\ddot{x}_g \\ y &= Cz + Df + v \end{aligned} \tag{2.4}$$

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

$$\begin{aligned} A &= \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ M^{-1}\Gamma \end{bmatrix} \quad E = -\begin{bmatrix} 0 \\ \lambda \end{bmatrix} \\ C &= \begin{bmatrix} -M^{-1}K & -M^{-1}C \\ I & 0 \end{bmatrix} \quad D = \begin{bmatrix} M^{-1}\Gamma \\ 0 \end{bmatrix} \end{aligned} \tag{2.5}$$

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 and intensively studied for better selection of the input voltage that must be applied to the MR damper to achieve the maximum performance (Dyke and Spencer, 1997 ; Jansen and Dyke, 1999 ; Oliveira *et al*., 2008). In the present numerical study a Clipped Optimal control will be used as shown in Fig. 2.2.

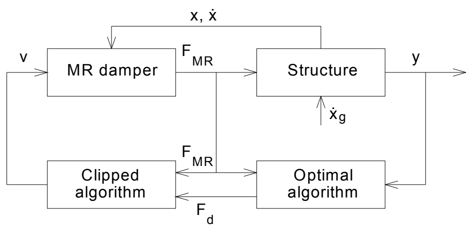


Figure 2.2. Clipped Optimal controller

This strategy consists of a Bang-Bang (on-off) controller that causes the damper to generate a desirable control force which is determined by an "ideal" active controller (in state feedback form). A force feedback is used to produce the desired control force f_d, which is determined by a linear optimal controller $K_k(s)$, based on the measured structural responses y and the measured damper force f_c. The linear controller is obtained with a LQG strategy (in this study).

Only applied voltage v_a can be commanded and not the damper force. The algorithm for selecting the voltage is $v_a = v_{max} H\,(f_d - f_c)\, f_c$ in which v_{max} 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 f_c equals the desirable force f_d, the voltage applied remains the same. When the magnitude of the force fc is smaller than the magnitude of f_d 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.

3. EXPERIMENTAL SETUP

According with the scheduled research program (Barros, 2008), the next stage was related with study the experimental dynamic behaviour of a 3DOF scaled metallic load frame with and semi-active devices. The structural setup was developed to allow semi-active control that was performed with a MR damper connected horizontally at the first floor level.

The experimental scaled building is a single bay three-storey frame (three degree of freedom in shear frame configuration) with the columns at the corner having the same stiffness as shown in Fig 3.1. The columns are made of aluminium 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.

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

$$M = \begin{bmatrix} 3.65 & 0 & 0 \\ 0 & 3.65 & 0 \\ 0 & 0 & 3.65 \end{bmatrix} (kg) \quad K = \begin{bmatrix} 5820 & -2910 & 0 \\ -2910 & 5820 & -2910 \\ 0 & -2910 & 2910 \end{bmatrix} (N/m) \tag{3.1}$$

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.

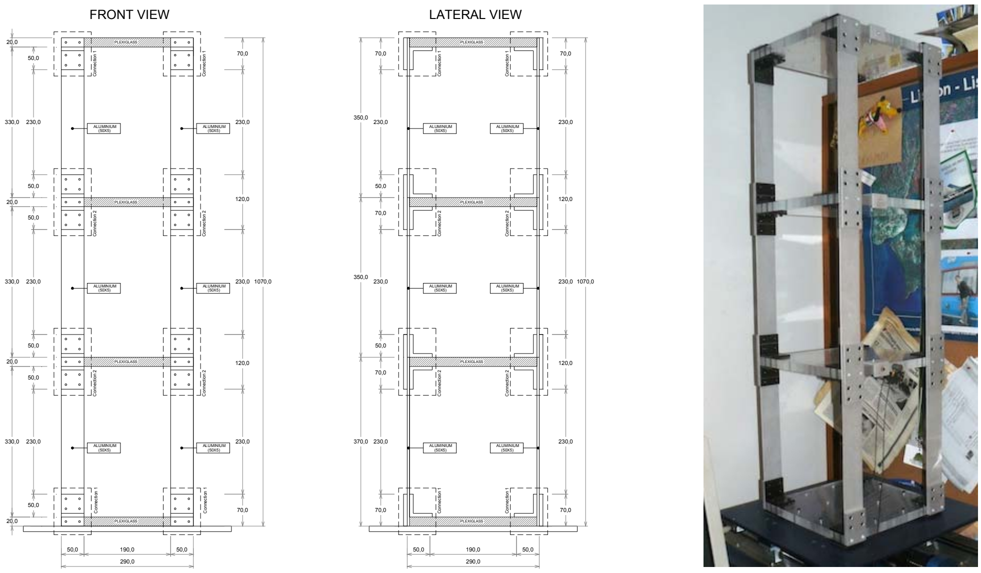


Figure 3.1. Metallic scaled frame (FEUP): geometrical properties and perspective view

This experimental frame located at FEUP-Covicocepad Lab, can be forced dynamically using the Quanser shaking table II as the dynamic loading actuator.

Figure 3.2. MR damper attached to the experimental metallic frame

To study the semi-active control strategy a small MR damper was placed at the first floor level attached to the frame and rigidly attached to the shaking table as shown in Fig 3.2. To acquire the damping force generated during the experimental tests a load cell is placed in the MR damper support system.

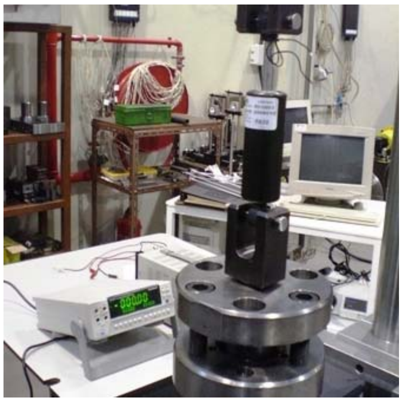
Figure 3.3. RD-1097-01 MR damper from Lord Corp.

The parameters of the MR damper shown in Fig. 3.3 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 Behaviour

To study the behaviour 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 as shown in Fig. 3.4, 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. Therefore, a set of frequencies (0.5, 1.0, 1.5 and 2.0 Hz), amplitudes (2, 4, 6, 8 and 10 mm) and current supplies (0.0, 0.1, 0.2, 0.25, 0.5, 0.75, 1.0 and 1.5 A) were used to complete the test program (Barros *et al*., 2009).



Parameter	Value
Extended length	208mm
Device stroke	±25mm
Max. Tensile force	4448N
Max. temperature	71ºC
Compressed length	155mm
Response time	<10ms
Max. Current supply	2A

Figure 3.4. Magneto-rheological damper RD-1005-03 test setup at FEUP

Typical results of this setup of the experimental research are shown in Fig. 3.5 and Fig. 3.6. The variable current tests demonstrate that increasing the input current implies an increase in the force required to yield the MR fluid and a plastic-like behaviour in observed in the hysteretic loop. In the frequency dependent test is observed that the maximum damping force increases with the frequency due to large plastic viscous force at higher velocity.

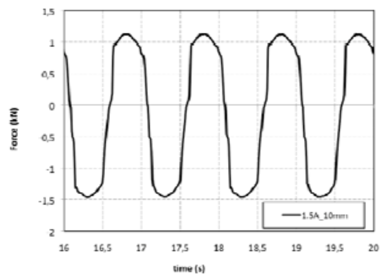


Figure 3.5. MR damper RD-1005-03
Force-Time History (1.5 A and 10mm).

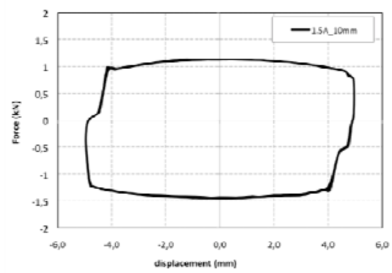


Figure 3.6. MR damper RD-1005-03
Force-Displacement curves (1.5 A and 10mm).

In order to simulate the Bouc-Wen model of a MR damper behaviour a simple MATLAB/SIMULINK block diagram was developed (Barros *et al*., 2009).

The same procedure was used to obtain the rheological behaviour of the RD-1097-01 MR damper. This 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:

$$\alpha(I) = 72.80I^3 - 42.88I^2 + 14.83I + 0.29$$
$$c_d(I) = -9.37I^4 + 10.22I^3 - 4.33I^2 + 0.89I + 0.02 \quad (3.2)$$

And the current independent parameters are: k_0= 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, Shen *et al.* (2007).

3.2. System Identification

An impulse hammer test was carried out in order to obtain the dynamic behaviour 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. The desired frequency response functions (magnitude and phase) for each input/output measurement are shown in Fig. 3.7-3.9.

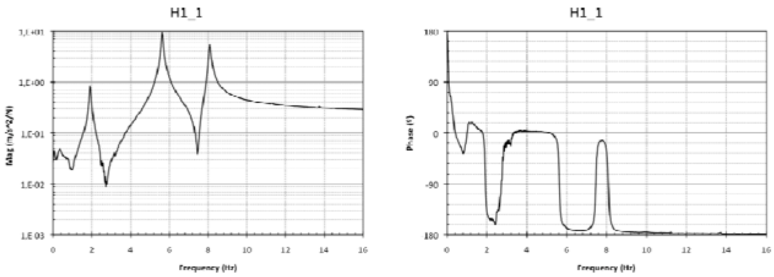


Figure 3.7. FRF magnitude and phase of H1_1

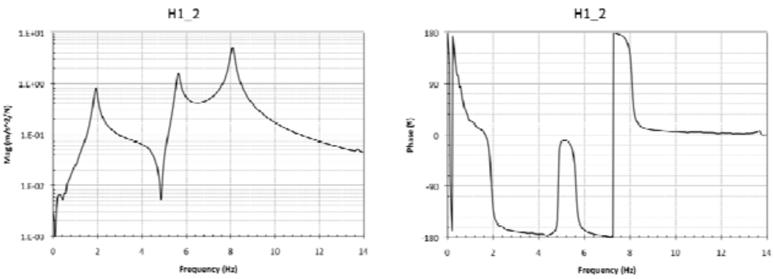


Figure 3.8. FRF magnitude and phase of H1_2

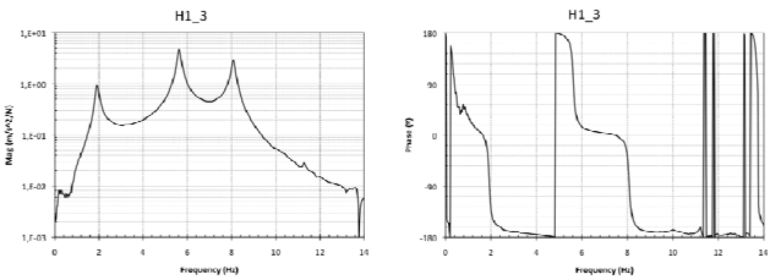


Figure 3.9. FRF magnitude and phase of H1_3

The parameters of the scaled frame were then obtained based on the data provided by these functions and are tabulated in Table 3.1.

Table 3.1. Parameters of the scaled frames

	Frequency	Damping	Modal Participation
Mode 1	1,913986	0,03157	34,43248
Mode 2	5,627778	0,01198	35,25975
Mode 3	8,086245	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 horizontal floor displacement was selected as the parameter (output) to verify the efficiency of the control law. Some results of this numerical analysis are plotted in Fig. 4.1-4.2 for uncontrolled and semi-active controlled scenarios.

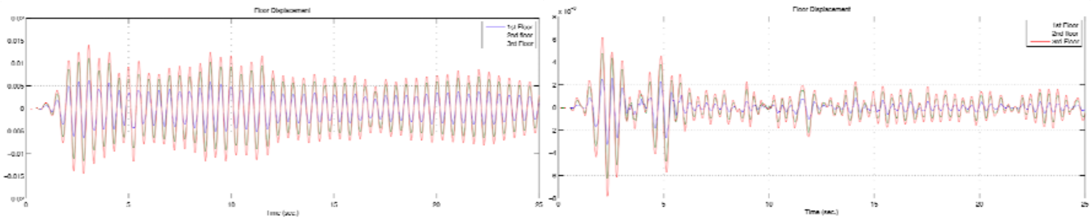


Figure 4.1. Uncontrolled response without MR damper and with MR damper @ 0.0A (passive ON)

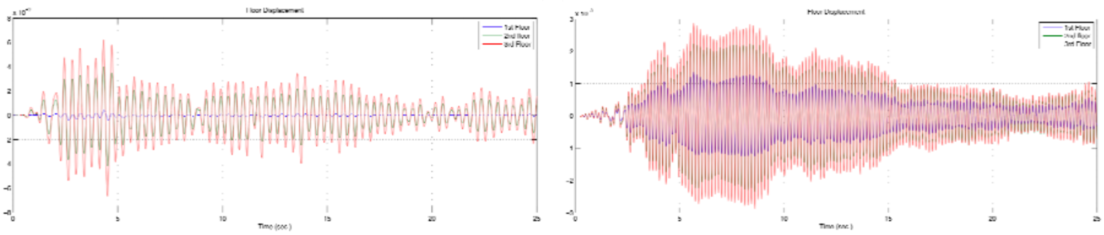


Figure 4.2. Uncontrolled response with MR damper @ 0.25A (passive ON) and Controlled response with MR damper (semi-active ON)

The structure response plot shown in Fig. 4.1 (left) was obtained without any device connected to the scaled frame (free 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. 4.1 (right). It is clear that a significant displacement reduction is obtained even with the MR damper in passive mode.

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. 4.2 (left), the first floor displacement was considerably reduced 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 displacement was again plotted as shown in Fig. 4.2 (right).

As expected, the semi-active control based on the Clipped Optimal algorithm was successfully applied. The floor lateral displacements of the building were reduced significantly during the earthquake duration.

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.

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