Experimental validation of a semi-active control system based on magnetorheological dampers

M. Spizzuoco, A. Occhiuzzi & G. Serino  
Department of Structural Analysis and Design,  
University of Napoli Federico II, Italy

Abstract

Structural active control systems have not yet completely passed the theoretical stage and only in few cases all over the world it has been possible to obtain a full experimental validation. At the moment, there is a lack of experimental evidence confirming the theoretical concepts shown in a quite large scientific literature. The present paper describes the experimental activity related to an effort to experimentally validate a control system based on a simple control algorithm and on a prototype semi-active magnetorheological damper. Starting from the definition of the proper control law and the analysis of the behaviour of the prototype semi-active device, the experimental activity comprised many shaking table tests on a 4-story steel frame which allowed to compare the structural response of the controlled structure to the corresponding behaviour in the case of classical passive dampers.

1 Introduction

Structural control, as a tool to reduce the response under strong external excitations such as earthquakes, is at the moment the subject of big research efforts, both theoretical and experimental. In the field of civil structures, however, there is still an urgent need to validate concepts found in the relevant literature by real-scale experimental activities. Semi-active devices are typically passive elements capable of self-adjusting their own mechanical properties in real time according to properly chosen criteria. Therefore, these devices, passive but “smart”, need an operational logic – the control algorithm – which drives
their instantaneous behaviour according to a desired final effect. Classical control algorithms have been developed in scientific fields different than structural engineering and, therefore, the application of many of them “as is” is almost always not possible.

Inaudi & Hayen [1] proposed a simple control logic for a semi-active control system (Figure 1). The semi-active device, which can be considered an extension of a classical Maxwell element, represents a variable-damping brace (VDB) to be installed as a smart brace in a building structure. The control logic is intended to maximize the extraction of energy from the main structure, by locking the VDB’s viscous damper in most of the time to transfer energy from the structure to the elastic brace, and unlocking it during short time intervals where the energy stored in the elastic element is dissipated in the damper. These short intervals have a fixed duration and begin immediately after a relative minimum or maximum in the motion \( x_f(t) \) of the points of attachment of the VDB on the hosting structure. For proper operations of the control system, as the duration of unlocking phases is selected equal to the undamped natural period of the VDB system, the latter must have a natural frequency much higher than that of the controlled structure and a damping ratio during unlocking intervals close to 1, in order to achieve a fast energy dissipation without force oscillations. On the other hand, during locking phases the damping ratio of the VDB system must be selected quite large so that the VDB’s deformation occurs mostly in the spring. The analytical formulation of the above control logic was shown by Inaudi & Kelly [2]:

\[
\begin{align*}
&\text{if } F_d(t) \cdot \dot{x}_f(t) > 0 \quad \text{then } C_d(t) = C_{d,\text{max}} \\
&\text{if } F_d(t) \cdot \dot{x}_f(t) < 0 \quad \text{then } C_d(t) = C_{d,\text{min}}
\end{align*}
\]

(1)

where the product of the damper’s force \( F_d(t) \) by the velocity \( \dot{x}_f(t) \) represents the power flow from the main structure to the device and \( C_{d,\text{max}} \) and \( C_{d,\text{min}} \) are the selectable viscous constants of the 2-stage device.

![Variable-damping system](image)

Figure 1: Variable-damping system.

2 Implementation of a semi-active control system

The idea expressed in the introduction has been investigated by the authors and applied to the semi-active control system of a steel frame structure. Indeed, for
this kind of structure, quite often equipped with bracing to resist lateral forces, the “smart” system seems to be quite effective. It is composed by three parts: the elastic brace, the dissipation device representing the link between the brace and the hosting structure and a control algorithm.

The elastic element $k_b$ of Figure 1 can be provided by an additional column, whereas the idea of a time-varying properties damping element is more difficult to implement. From this perspective, magnetorheological (MR) dampers represent an attractive way to materialize the concept of time-varying damping device: by using low-power electrical currents, the rheological properties of the MR fluids can be varied so as to achieve a wide range of physical behaviours (Serino et al. [3], Occhiuzzi & Spizzuoco [4]).

The MR fluids are materials that respond to an applied magnetic field with a sharp change in the rheological behaviour: their essential characteristic is the ability to reversibly change from free-flowing viscous liquids to semi-solids having a yield strength controllable in milliseconds when exposed to a magnetic field. The intensity of the magnetic field varies the rheological properties of the fluid and, in turn, the dynamical properties of the damper using MR fluids. The Bingham model, which is commonly considered in literature to describe the behaviour of a MR damper, can be derived from the Bingham model for the MR fluid through the study of an axisymmetric model of the flow as shown by Spizzuoco & Serino in [5], and Yang et al. [6]:

$$F_d = C_d \cdot U + F_{dy}(i) \cdot \text{sgn}(U)$$

(2)

The total force in the MR damper can be expressed as the sum of two components due to the fluid viscosity and to the magnetic field-induced yield stress, respectively. $U$ is the relative velocity between the damper’s ends, $C_d$ the viscous damping constant, $F_{dy}$ the variable plastic threshold which is controlled

![Figure 2: Variable-damping system.](image)
by the applied magnetic field and \( i \) is the current in the coils inside the MR damper which generates the magnetic field. For a semi-active MR damper, by varying the current in the coils from zero to a maximum value, it is possible to obtain a fairly wide range of plastic thresholds from a minimum value \( F_{dy,min} \) due to the friction force of the gaskets to a maximum value \( F_{dy,max} \) due to magnetic saturation.

In the case of the semi-active control system shown in Figure 4, the control logic expressed by eqn (1) can be turned in the following (Occhiuzzi & Serino [7]):

\[
\text{if } F_d(t) \cdot \dot{x}_f(t) > 0 \quad \text{then } F_{dy}(t) = F_{dy,max} \\
\text{if } F_d(t) \cdot \dot{x}_f(t) < 0 \quad \text{then } F_{dy}(t) = F_{dy,min}
\]

(3)

i.e., the variable-damping system, made up by the MR damper, the mass \( m_b \) and the elastic brace of stiffness \( k_b \), can be used to temporarily store a fraction of the energy flowing from the ground to the structure during an earthquake and to release that energy during fast dissipation processes. During the storing phases, corresponding to time intervals where the power flow from the structure to the control system is positive, the latter has to be tuned so as to achieve the maximum possible strain in the elastic element. Therefore, the value of variable plastic threshold \( F_{dy} \), controllable by the applied magnetic field, has to be set as high as possible. When the sign of the power flow changes to negative, by switching \( F_{dy} \) to its minimum value the dissipation phase is invoked to let the MR damper dissipate the elastic energy stored in the brace. If the control system is properly designed, the spring displacement \( x_b \) goes to zero and the elastic energy stored therein is dissipated in a time interval that is short if compared to the natural period of the frame.
3 Performance and potentialities of a prototype MR damper

In the framework of the EU funded SPACE (Semi-active and PAssive Control of the dynamic behaviour of structures subjected to Earthquakes, wind and vibrations) Research Project, four 50 kN semi-active MR dampers (Figure 5) have been manufactured by Maurer Söhne (Munich, Germany) and experimentally tested to evaluate the characteristics of their operation.

The experimental campaign included imposed displacement tests at different frequencies (ranging from 0.5 to 4 Hz) and driving currents (ranging from 0 to 3 A). The analysis of the experimental data gave an almost linear variation of $F_{dy}$ from $F_{dy,\min} = 0.6$ kN (at $i = 0$ A) to $F_{dy,\max} = 28$ kN (at $i_{\max} = 3$ A), whereas the investigation of the force-displacements loops corresponding to different test frequencies and driving currents have shown a dependence of the viscous parameter $C_d$ on the feeding current and consequently a non-linear dependence of the viscous damping component of $F_d$ on the velocity. The following numerical model (Occhiuzzi et al. [8]):

$$F_d = C(i) \cdot |U|^{\alpha(i)} \cdot \text{sgn}(U) + \left[F_{dy,\min} + \left(F_{dy,\max} - F_{dy,\min}\right) \cdot \frac{i}{i_{\max}}\right] \cdot \text{sgn}(U) \quad (4)$$

Figure 4: Scheme of the semi-active control system.

Figure 5: The prototype MR dampers.
turned out to closely fit the experimental data of the tested MR dampers. The least-square interpolating curves $C(i) = 5.5 + 5.0 \cdot i$ [kNs/m] and $\alpha(i) = 0.0795 \cdot i^2 - 0.3475 \cdot i + 0.9$ of the values of the mechanical parameters $C$ and $\alpha$ are shown in Figure 6.

To the aim of experimentally characterize the time delays of the control chain and then to verify the promptness of the semi-active MR device, four elastic coil springs connected in parallel, simulating an elastic bracing system, were included in a first experimental set up: they were inserted between the MR damper and the rigid element representing the fixed restraint (Figure 7). The semi-active tests were performed by using a dedicated electronics consisting of a real time National Instruments CPU, a digital acquisition board with 8 inputs and 2 outputs, the environment Labview Real-Time, and an operational power supply from Kepco Inc. (New York, USA).

Figure 6: Viscous parameters of tested MR dampers.

Figure 7: Experimental set up.
An energy-based algorithm following the logic given in eqn (3) was applied during the imposed harmonic displacement tests. It commands a “switch off” of the damper (0 A in the damper’s circuit) when a relative minimum or maximum of the damper displacement occurs, and a “switch on” of the damper (3 A in the damper’s circuit) when the energy dissipated by the springs in the off phase is over. Figure 8a shows a magnification of some time histories recorded during the imposed harmonic displacement test performed at 2 Hz and 20 mm amplitude. The recorded signals are the absolute displacement of the damper, the relative displacement of the damper’s ends, the total force in the damper and the current inside the damper. In Figure 8, the path described by the points marked with capital letters from A to G on the time-history of the MR damper displacement (Figure 8a) and in the force-displacement plane (Figure 8b) has been shown, to better understand the operation of the MR damper driven by the proposed algorithm:

A – The MR damper is on (3A) and starts moving because the plastic threshold \( F_{dy} \) is reached. From this point the viscous component is clearly visible in the force-displacement cycle.

B – Following a relative minimum of the damper absolute displacement and a switch off command to the device, the current begins to decrease, which will cause the start of a sharp change of the force in the damper. This is the beginning of the dissipation activity of the semi-active device.

C – The MR damper begins to react before the current inside the damper reaches the commanded value (0 A).

D – The current reaches the nominal commanded value within a tolerance ± 5%.

E – The elastic springs have dissipated all the stored energy and, after a switch on command issued by the algorithm to the device, the current begins to increase and the springs start to accumulate elastic energy again.

F – The MR damper begins to stop its relative displacement before the current inside the damper reaches the commanded value (3 A).

G – The current reaches the 95% of the maximum value commanded by the algorithm (3 A), the relative displacement inside the damper is practically zero and the springs keep accumulating elastic energy.

In Figure 8a \( \tau_{\text{off}} \) and \( \tau_{\text{on}} \) are the total time delays, i.e. the time intervals required by the current to reach 5% and 95% of the nominal value set by the algorithm, respectively in the on-off and the off-on phase. A statistical analysis of experimental data clearly shows that these delays are practically independent on the test frequency and their mean values are about 10 ms in the on-off phase and about 13 ms in the off-on phase. Finally, \( \tau_{cl} \) represent the commanded operation time decided by the algorithm and \( \tau_{cl,\text{effective}} \) is the time interval comprising the beginning and the end of the 0 A phase of the damper. They have approximately the same duration of about 40 ms and are offset by about 10 ms.
4 Experimental validation of the semi-active control system on a steel building

In the framework of the SPACE Project, a steel frame structure, designed by ENEL and ENEA and manufactured by ISMES in Seriate (Italy), has been equipped with the four semi-active MR dampers shown in the previous section.

It is a 4-storeys steel structure composed by 6 vertical columns (HE100B) 4.5 m high, bolted on a base frame manufactured using HE140B beams. Four horizontal frames (HE100B) can be bolted at the columns, with an interstory distance of 0.9 m or 1.1 m. The total weight of the steel frame is 37 kN. Each

![Graph showing the semi-active operation of the MR damper](image)

Figure 8: Semi-active operation of the MR damper: test at 2 Hz and 20 mm.
horizontal frame, which is 3.3 m x 2.1 m, can support up to 8 reinforced concrete masses, each weighting 12.8 kN (a total number of 20 masses is available).

The steel used for the MISS has an ultimate strength of 430 MPa, a yield strength of 275 MPa and a Young’s modulus of 200,000 MPa. The first mode damping ratio of the steel frame was experimentally evaluated equal to 1.7%, and the modal frequencies of the unbraced structure are: \( \omega_1 = 13.80 \text{ rad/s}; \omega_2 = 53.44 \text{ rad/s}; \omega_3 = 120.48 \text{ rad/s}; \omega_4 = 191.93 \text{ rad/s}. \)

Then, four flexible braces of properly chosen stiffness, each equipped with a MR damper, have been mounted on the structure (Figure 9a) along its short edge (transverse) direction. The braces are made of the steel profile HE200A for the 1st level device and IPE180 for the 2nd level device. Figure 9b also shows the experimental set up of the building, with all the instrumentation used for the semi-active control.

Besides considering a semi-active control configuration, where the MR dampers are fed with a time-varying current input signal according to energy-based algorithm, the frame structure has been tested in an uncontrolled unbraced configuration, a "passive off" (0 A current) control configuration and a "passive on" (2.5 A current) control configuration. Three accelerograms, two natural and one artificial, have been adopted for the shaking table tests: the Tolmezzo (medium-rigid soil) record of the 1976 Friuli (Italy) earthquake, the second (N-S) component (Northridge) recorded in 1994 at Sylmar County Hospital parking lot, and a synthetic accelerogram generated according to Eurocode 8 for soft (CGS) soil conditions.

Figure 9: MISS structure and its experimental set up.
Figure 10 shows the experimental time histories of the relative displacements recorded at the 2nd floor of the tested building for both the "passive off" configuration, the "passive on" configuration and the semi-active configuration under the Tolmezzo record at -1dB attenuation level. The response reduction in terms of maximum displacement in the semi-active case is about 35% with respect to the "passive on" configuration. On the other hand, the absolute accelerations recorded at each floor in the semi-active configuration don’t exceed those corresponding to the "passive on" case.

![Figure 10: Tolmezzo -1dB: relative displacement of the 2nd floor.](image1)

![Figure 11: Tolmezzo -1dB: absolute acceleration of the 4th floor.](image2)
The behaviour of the semi-active system can be interpreted from an energy balance perspective. From the equation of the motion of the system:

\[ M \cdot \ddot{x}(t) + C \cdot \dot{x}(t) + K \cdot x(t) = -M \cdot x_g(t) \]  

(5)

Figure 12: Comparison of energies corresponding to different configurations.
it is possible to derive the following energy balance:

\[ E_e(t) + E_k(t) + E_d(t) = E_i(t) \]  

\[ E_e(t) = 0.5 \cdot x^T \cdot K \cdot x \]
\[ E_k(t) = 0.5 \cdot \dot{x}_t^T \cdot M \cdot \dot{x}_t \]
\[ E_i(t) = \int_0^t \dot{x}_t^T \cdot M \cdot d \dot{x}_g \]

where \( x_t = x + x_g \), \( E_e \) is the elastic stored energy, \( E_k \) is the absolute kinetic energy, \( E_i \) is the seismic input energy, and \( E_d \) is the dissipated energy. In the passive off configuration of the tested building, under the action of the Tolmezzo earthquake base acceleration, a total energy of about 7 kJ was input into the structure (Figure 12). Most of this energy was damped out by the MR dampers in their passive, 0A state, but a peak of about 2kJ of elastic+kinetic energy was reached many times in the strongest phase of the base excitation. In both the passive on and semi-active configurations of the control system, the total input energy reduced to about 3 kJ. This is in agreement with the trend of the input energy spectra of recorded earthquakes, whose ordinates usually increase almost linearly with the period \( T \) of the structure, for \( T < 1s \) (De Luca & Serino [9]). However, the sum of elastic+kinetic energy reached a peak of about 1.5 kJ in the passive on configuration and a maximum value of about 1.2 kJ during semi-active operations. In other words, the particular semi-active logic adopted to drive the dampers does not change the global dynamic behaviour of the structure, compared to a rigid-linked bracing system but, forcing the damping phases in selected time intervals, is successful in optimising the amount of energy dissipated. As a result, the semi-active configuration of the control system reduces the amount of structural displacements without trading off increased acceleration peaks.

5 Conclusions

The effective implementation of a relatively simple, but effective, control system on a full scale structural model has been described in the previous sections. The basic idea of a time-varying parameters damping element has been materialized through the adoption of a magnetorheological damper driven by a specific control algorithm. The tests on the control system have shown the feasibility of the control system proposed, its behaviour and promptness to comply to the driving algorithm. The shaking table tests on a steel frame mock-up have demonstrated, and therefore validated, the effectiveness of the proposed control system in reducing the structural response under large excitations.

References


