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# RE-CENTERING CAPABILITY EVALUATION OF SEISMIC ISOLATION SYSTEMS BASED ON ENERGY CONCEPTS

**Christian BRAUN [1], Renzo MEDEOT [2] and Peter HUBER [3]**

## SUMMARY

The Project SPACE (**S**emi-Active and **PA**ssive **C**ontrol of the Dynamic Behaviour of Structures Subjected to **E**arthquakes, Wind and Vibrations) - Contract N°:EVG1-CT-1999-00016 - represents the result of an initiative of nine organizations from five different European countries and is supported by the Environment and Sustainable Development Programme of the European Commission Research Directorate General (Contract N°:EVG1-CT-1999-00016).

The protection of transport infrastructures, industrial plants and strategic buildings from earthquake damage is of paramount importance, particularly regarding the southern areas of the European Union. In addition, there is a widely felt need to eliminate the disturbances produced by traffic and other unwanted sources of vibration affecting equipment of ever increasing sensitivity and sophistication.

The project's main objective is that of substantially contributing to the solution of the above-mentioned problems through the development of the following systems:

- an innovative semi-active type of damper based on a new magneto-rheological (MR) fluid with enhanced stability, especially suited to high-demand applications in structural vibration control;
- an improved passive floor-isolation system based on high-damping elastomeric bearings suitable for horizontal seismic inputs alone or in combination with vertical inputs from ground-borne vibrations.

The Project comprises ten Work Packages and its most remarkable feature is the multi-disciplinary nature, which required great co-ordination and co-operative efforts.

The Project SPACE completion dates 31st March 2003 The paper describes the goals attained, the scientific achievements, as well as illustrates one demo intervention and two cases of exploitation.

## INTRODUCTION

The scope of the SPACE Project comprises the mitigation of the undesired effects induced in different types of structures by earthquakes, windstorms and ground borne vibrations.

The above was achieved through the development of two distinct lines of devices.

[1] Managing Director, MAURER SÖHNE, Munich, Germany – E-mail : braun@mchn.maurer-soehne.de
[2] Consultant, Selvazzano, Italy – E-mail : medeot@iol.it
[3] Chief Engineer, MAURER SÖHNE, Munich, Germany – E-mail : braun@mchn.maurer-soehne.de

The first regarded an innovative, semi-active damper, based on a Magneto-Rheological (MR) fluid, suitable for highly demanding structural control applications.

The second dealt with a three-directional floor isolation type of device, suitable for passive control of vibrations induced by low and high frequency inputs (earthquake and traffic-induced respectively).

Additionally, the Project also needed the development of suitable materials (a stable MR-fluid and special rubber compounds) and a semi-active advanced system, as well as a series of algorithms for the different types of structures examined.

Due to space restraints, this paper focuses its attention on the semi-active dampers based on MR-fluid only.

The following describes the scenario the proponents of this project entertained at the time of its submission (Summer 1999).

Passive energy dissipation is gaining acceptance as a means of controlling the action of earthquake and wind loading on structures [19 to 24] and [28,29].

However, passive devices presently available, suffer from certain limitations, the most important of which is the impossibility of varying their intrinsic characteristics to meet the demands of actual input types. The latter are difficult to predict and, in practice, project design engineers often have to rely on compromise solutions.

Conversely, the semi-active control of the dynamic response of a structure is based on the damper's capability to modify its stiffness and/or damping characteristics while an external excitation is acting upon it, so as to eliminate the possibility of resonance and maximize energy dissipation.

This is achieved through the insertion, at appropriate locations of the structure, of special devices operated by electronic control system in accordance with a specific control algorithms requiring real-time acquisition of the response and/or external actions.

Therefore, semi-active control systems differ from passive ones by producing a temporary rather than permanent modification of the global mechanical characteristics of the structure.

Like completely active control systems, a hardware unit for processing acquired signals and actuation of control commands is required, but semi-active devices do not apply external forces on the structure. Thus, no possibility exists that dynamic instability may occur resulting in amplification instead of reduction of the structure response when control does not operate properly.

Studies [1 to 12] clearly indicate that a semi-active system adequately implemented allows a more effective reduction of dynamic response of a structure compared to that obtained adopting purely passive devices, and can provide results comparable to those obtained through completely active systems, with a very efficient response control under a wide frequency spectrum of dynamic actions.

One of the most promising possibilities of immediate applications for semi-active control systems is certainly represented by the reduction of wind effects on long-span or high-rise structures.

Wind action represents for such structural systems a problem conditioning the design, while their large flexibility and long fundamental periods significantly reduces practical implementation problems connected to the short intervals required for acquisition, processing and actuation of control signals. Adoption of variable damping devices in bridges has been first proposed and studied both in the United States [1] and in Japan [2].

The main types of semi-active device are: i) variable orifice dampers; ii)variable friction dampers and iii) electro- and magneto- rheological dampers. Variable orifice dampers rely on an external oil circuit containing electro-valves to allow adjustment of the effective damping coefficient. These devices have been assessed for bridges and structures [4 to 6 ].

The friction devices operate by adjusting the normal force on a friction interface. They have been evaluated by workers in USA [8] and Canada. As with most friction devices, there are likely to be problem of long term reliability ands consistency of performance.

The drawback that is common to all the above devices is the long reaction time (above 100 ms).

## DEVELOPMENT OF THE PROJECT

This section illustrates the various phases in which the SPACE Project is articulated, presenting in a logical and temporal sequence how said phases are developing.

In this manner, it illustrates the strategic function of each partner as well as the importance of their complementary interactions.

The objective of the *first Work Package*, leaded by Bilfinger Berger, was to define typical civil and industrial structures for which the adoption of structural control (SC) and/or floor isolation (FI) could be an efficient way to mitigate seismic risk or reduce structural sensitivity to dynamic effects due to wind and traffic.

The first step has been the formulation of criteria for the selection of representative structures with respect to high efficiency in the application of SC and/or FI devices.

After this process, it was undertaken to proceed with the examination and determination of those structures (for each task) in which the utilization of innovative SC and/or FI devices might provide a technical and economic advantage.

Typical applications are bridges, industrial and chemical plants (chimneys, tanks, control rooms, electrical equipment), and critical buildings (hospitals, emergency operation centres, museums and historical buildings).

*The second Work Package* objective were those of developing a control strategy and a related algorithm, as well as the design and manufacture of sensor arrays and control unit electronics.

After a deep examination of the preliminary results of the numerical simulations, it was decided to focus attention and research efforts on the “Energy” and “LQR” algorithms.

A close cooperation of Università di Roma 3 with TUS allowed to define the viability of the implementation of the above two algorithms firstly for the MISS mock-up and secondly for the in-situ test on the Forchheim footbridge.

The control software (developed in Labview language) has been developed, implemented and validated in order to be suited to the semi-active control of structures, using MR dampers.

The two control algorithms have been implemented in the control system software: Energy (mainly for control in the case of seismic application) and LQR (mainly for vibration control).

The efficiency of the control software has been established in shaking-table tests on a floor mock-up (MISS structure). Substantial reduction of accelerations for several earthquake records were found.

The efficiency of the control software has also been established in in-situ tests (Forchheim footbridge ).

*The third Work Package* represents the core of the entire Project inasmuch as the most adequate devices for reducing the effects of seismic, wind and traffic induced vibrations (as applicable) have been conceived, designed and manufactured for each of the selected structures.

Always within the framework of this Work Package, there is the development of a new MR-fluid suitable for applications in the field of seismic engineering; that is to say, one endowed with great stability vis-à-vis the passage of time.

The essential characteristic of magneto-rheological fluids is their ability to reversibly change from a free-flowing, linear viscous fluid to a semisolid with a controllable yield strength in milliseconds when exposed a magnetic field.

MR fluids typically consist of micron-sized, magnetically polarisable particles dispersed in a carrier medium such as mineral or silicon oil.

The interaction between the resulting induced dipoles causes the particles to form columnar structures, parallel to the applied field. These chain-like structures restrict the motion of the fluid, thereby the viscous characteristics of the suspension.

The energy needed to yield this chain-like structures increases as the applied magnetic field increases resulting in a field dependent yield stress. In the absence of an applied field, MR-fluids exhibit Newtonian-like behaviour [30].

Transition to rheological equilibrium can be achieved in a few milliseconds, allowing construction of devices with high bandwidth.

A MR fluid can be readily controlled with a low voltage (e.g., 12-24 V), current-driven power supply outputting only 1-2 amps.

Nonetheless, settling of the particles in the commercially available MR-fluids represents a serious problem, as it is detrimental to the device's performance in seismic engineering.

One of the goals of the SPACE Project was that of developing a time-stable fluid, in which the particles will not settle.

KTH has developed an MR fluid with good sedimentation stability and re-dispersing properties. Furthermore, the MR fluid shows good mechanical properties (i.e. high yield strength) when compared to other MR fluids.

Maurer Söhne has conceived, designed and manufactured several MR-dampers and two types are shown in Figures 1.1 and 1.2 below.


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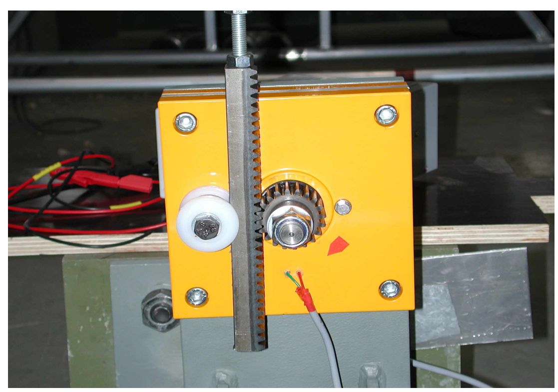

Fig.1.2 : Prototype of MR-revolving damper

With the subsequent Work Package 4, reliable numerical models of the analyzed devices have been implemented and validated on the basis of experimental results, with the aim of providing input data to the manufacturers and the designers of the structures.

The availability of reliable detailed numerical models of the device, essentially based on finite-element methodology, is necessary for the future improved and less costly design of such devices, as well as to evaluate the effects of the various parameters that might affect device response by minimising costly experimental efforts.

Moreover, the definition of simplified numerical models, based on simply rheological laws, is needed for the analysis of structures and components incorporating the innovative devices.

ENEA, in collaboration with Bilfinger Berger and Università di Roma 3, has developed numerical models of the MR devices and modeled in ABAQUS, MATLAB and ANSYS computer codes. ENEL, in cooperation with TARRC, concluded the implementation of the numerical model of the floor isolation devices of the control room. The *fifth Work Package* is similar to the previous one inasmuch as it deals with the implementation of reliable numerical models of the selected structures and mock-up as well as their validation based on experimental results. However, it has a different objective and requires specific competencies.

Indeed, models are necessary to correctly perform design evaluations for structures and components provided with the innovative devices.

Thus, reliable numerical models of the identified structures and components have been developed and validated based on the analysis of experimental data.

Numerical procedures have also been assessed (e.g. linear, non-linear analysis, modal combination rules, etc.)

The analysis efforts have been shared amongst some partners according to their specific interests and experience. Analyses have been carried out for all the structures selected, with and without the innovative devices.

Within the framework of the *sixth Work Package* – (*Tests on devices*) , the MR dampers produced by Maurer Söhne have been tested at ISMES laboratories in both passive and semi-active modes of operation. Tests on MR dampers have been performed with two different experimental configurations.

In the first configuration, the device was rigidly connected to the testing rig, whilst in the second configuration (see Figure 2) the device was connected through an elastic restraint element; the latter was included for verifying the application of the control system in a configuration representing a device + brace semi-active assembly, as it was in the MISS steel mock-up structure to be tested in WP7. Tests were carried out using different excitations.

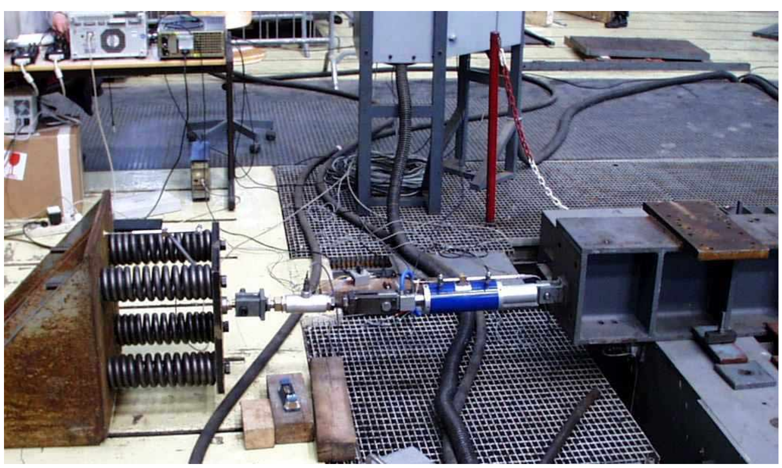

Figure 2: Characterization testing on linear MR-dampers

The *seventh Work Package*-(*Tests on structures and mock-ups*) concerns two tasks: the first wais dedicated laboratory testing, whilst the second regarded the on-site testing on the demo intervention.

Tests on the steel mock-up MISS equipped with MR-dampers manufactured by Maurer Söhne were successfully carried out during the second half of May 2002 (see Figure 3).


Figure 3: Shaking-table tests on mock-up MISS equipped with MR-dampers

The results were required for validation of the numerical models of devices and structures, evaluation of the Technical benefits of Structural Control and Floor Isolation, and the preparation of a User Manual.

The objective of the *eighth Work Package* was the quantification of the technical and economical benefits made possible by using the new innovative devices regarding different types of structures.

A technical comparison of structures with and without the application of SC and / or FI were made taking into account design concepts, structural behaviour (short- and long-term), seismic risk (collapse), service conditions and maintenance efforts.

For application of the semi-active MR dampers in the field of retrofit of existing structures a significant reduction of repair costs has been calculated in comparison to conventional methods such as strengthening of members. In this special case a cost reduction of 80% has been achieved which will be in the range of about 50% for other types of structures.

For application of semi-active MR dampers in new structures an average cost reduction of about 12% has been calculated in comparison to the structure equipped with conventional passive devices. Additional maintenance costs are not expected.

The objective of the *ninth Work Package* was to prepare a “User Manual” and to provide potential designers with a practical tool for the implementation of innovative passive/semi-active technologies for vibration control of structures subjected to various natural dynamic sources (earthquakes and wind) and artificial (traffic, railroads, machinery, etc.).

## DEMO INTERVENTION AND EXPLOITATION

To demonstrate the efficacy of the semi-active systems developed within the framework of this project, the Steering Committee deliberated to carry out a demo-intervention on the Forchheim Pedestrian Bridge (L=112 m) in Germany.

Figure 4 below shows the pedestrian bridge as well as the tuned mass equipped with the semi-active MR-damper of the revolving type.


Figure 4: Pedestrian bridge in Forchheim equipped with semi-active MR-damper

It is worth mentioning that, within the framework of SPACE Project, there has been a first case of exploitation, i.e. the Abandoibarra Pedestrian Bridge (L=142 m) in Bilbao – Spain, which has been particularly tasking.

Also, the 3-D isolators found an interesting application on the anti-seismic protection of an ancient Roman vessel discovered near Ercolano (Naples).

## GOALS ATTAINED AND SCIENTIFIC ACHIEVEMENTS

As already anticipated, the Technical-Scientific Objectives of the project were the development of innovative systems based on:

a- semi-active control of the vibrations induced by earthquake and wind by means of magneto- heological damping devices;

b- very stable magneto-rheological fluid, particularly suitable for applications in seismic engineering

c- 3-D floor isolation system

The attainment of the main project objectives has also generated a series of collateral technical and scientific outcomes, namely:

1.- two control algorithms ("*LQR*" and "*Energy-based*");

2.- one data acquisition system and one dedicated semi-active control system for the demo- intervention

3.- three numerical models implemented in the most diffused finite element codes for structural analysis, namely ABAQUS, ANSYS and MATHLAB

4.- seven sophisticated numerical models of structures incorporating semi-active devices (four bridges, two edifices and one chimney)

5.- one numerical model of structures incorporating 3-D devices

6.- advanced testing methods for passive and semi-active devices on shaking table, as well an in-situ testing

## CONCLUSIONS

1. The present orientation of the designers is towards conceiving ever more daring structures as well as asking for greater margins of safety and comfort. By now, passive systems have reached a level next to the maximum theoretical one and show no foreseeable capability to furnish a satisfactory response to the future requirements of design engineers.
2. The above opens by itself a market for sophisticated technologies. The innovative semi-active dampers, based on a magneto-rheological (MR) fluid, are precisely suitable for highly demanding structural control applications.
3. This semi-active damper can be readily controlled with a low voltage (e.g., 12-24 V), current-driven power supply outputting only 1-2 amps, with reaction time lesser than 10 ms. This represents a very innovative feature, in that the semi-active dampers found on the market and in literature show a reaction time at least one order of magnitude higher.
4. The test campaign and the mathematical simulations conducted in the framework of the SPACE Project have proven suitability of MR-dampers for seismic applications in both bridges and edifices
5. The semi-active damper is particularly cost effective in retrofit projects.

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