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Design and Experimental Tests On Electro-inductive Dissipators

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Abstract

The devices, described in the work, represent the first prototypes of a research project, currently in progress, to investigate the potentiality and the applicability of electro-inductive dissipators in passive, semi--active and eventually active control systems for civil structures protection.

The research project on electro--inductive dissipators (that in general can be called DECS = Devices based on Electro-inductive principle for the Control of Structures), partially funded by the Italian Ministry of University and Research (MURST), has the following partners:

- Alga, that is the industry for the devices manufacturing and for the co--ordination of the research activities;
- University of Pavia, that has the task to identify the possible applications of the innovative devices in passive, semi--active and active control systems by theoretical studies and experimental tests on scaled models;
- Polytechnic of Milano, that has to develop the theoretical studies concerning the electromagnetic design of DECS and to perform some tests on suitable prototypes;
- ENEA, that is involved on the experimental verification of the devices installed on structures excited by a shacking table.

The paper describes the design and the experimental tests performed on passive devices.

1. Electro--inductive devices

The principle of operation of the electro--inductive devices [1] can be one of the following:

- generation of electrical power from vibration power, using the motion caused by external excitations due to earthquakes as primary energy source at the device mechanical input, in order to limit and damp the motion (passive and semi--active DECS [2]
- regulation of sign and amount of the instantaneous power flow exchanged between earthquake and device, in order to achieve a real time control of the vibration modes of the structure to be protected (active DECS).

The devices, in fact, must be located on structures and connected between two points in relative movement during the earthquake excitation.

In case of non--active devices, thanks to these movements, the apparatus develops electric energy (as in the electrical generators), subsequently dissipated into heat: if the energy conversion is uncontrolled, this is the basic operating principle of passive electro--inductive dissipators; if the energy dissipation is modulated (usually by employing low power level controlling auxiliary devices), the apparatus is called semi--active dissipator.

The basic device scheme of a non--active device includes a part equipped with permanent magnets, in order to create a magnetic field, and another part, in relative motion with respect to the previous one, containing the induced electric circuit and, in case, connected to an external circuit: the selection of which parts are fixed or moveable depends on design choices, nature on the device, level of power to be dissipated; the use of permanent magnets, instead of a current excitation system, is preferable because of its simplicity, the secure and ready availability of the magnetic field and the consequent higher reliability features.

The dissipation level depends on the relative velocity of the electric circuit as regards to the magnetic field. Being the response of devices related to the operating linear velocity v, the electro--inductive dissipators can be compared with the viscous dampers; for both the devices the response law can be
expressed by the following equation:

$$F = c \times v^{\alpha}$$

where: F = response force, c and α suitable constants to model the device behaviour.

When the velocity is small, the reaction force of the devices is negligible: this is fundamental to allow the slow movements of the structures (for example thermal expansion or contraction), by the contrary when the motion is fast the response increases and the dissipation effect is required.

Compared to standard dampers, the electro-inductive devices require very low maintenance (limited to the anchorage to the structure), no ageing effects, no limitation on cycle life and low scattering on the response. The operating velocity range definition is the basic requirement for the electro--inductive devices design; for seismic applications, a reasonable average reference value for the earthquake velocity is approximately equal to $v_{ref} = 0.5$ m/s.

From preliminary theoretical investigations, the previous velocity value seems to be an important constraint for obtaining a reasonable dissipation for electro--inductive devices.

Once the devices basic operating velocity has been selected, two possible dissipator schemes have been investigated [3]:

- a linear dissipator, basically composed by two plates with permanent magnets and an internal plate of conductive, non magnetic material that moves between the previous two. This solution has the advantage to be very simple, both as regards manufacturing and mechanical connection to the structures, but it is very difficult to find a reasonable and simple way to increase the relative velocity between the fixed and movable components, too poor in order to obtain satisfying performances;
- the second DECS type is a rotating system where the linear earthquake motion is converted into a rotational one through a screw: the advantage of this solution is the possibility of amplifying the relative velocity by a suitable selection of the ratio between linear and rotational motion. An optimal design of the screw must tend to increase as much as possible the velocity ratio, at the same time limiting the friction between screw and rotating component; to this aim, special low friction materials must be adopted for the screw and the rotating part.

In the research project both linear and rotating device have been investigated, in order to fully understand and experimentally verify advantages and drawbacks of each solution.

2. Designed and tested electro--inductive devices

All the prototypes have been tested using an MTS test machine, available at ALGA laboratory, using sinusoidal and triangular displacement signal with different frequencies and amplitudes [4].

2.1 Linear dissipator

The linear dissipator is shown in the figure 1.

Figure 1: Linear DECS

Many tests have been performed in order to characterise the device response.

The aim of the tests is to calculate the device reaction for very slow movements (i.e. friction of the device) and the device responses cycle in term of reaction force and displacement for fast test to evaluate the energy dissipation due to electro--inductive effects.

The tests were conducted using a frequency range form 1/200 to 2 Hz and amplitudes from 10 to 80 mm. The response force is equal to approximately ± 1 kN. The relative small value of the reaction force is due to the size of the designed linear dissipator and to the low relative velocity between the fixed and movable components.

The device, anyway, showed response cycles shapes close to the theoretical ones: an ellipse (for sinusoidal input displacements) and a rectangular (for triangular input displacements).

2.2 Rotating device

The expected small relative velocity between the fixed and movable parts due to a seismic excitation, suggested the design of a system to increase the velocity by an endless screw. The rotating device scheme is shown in the figure 2.

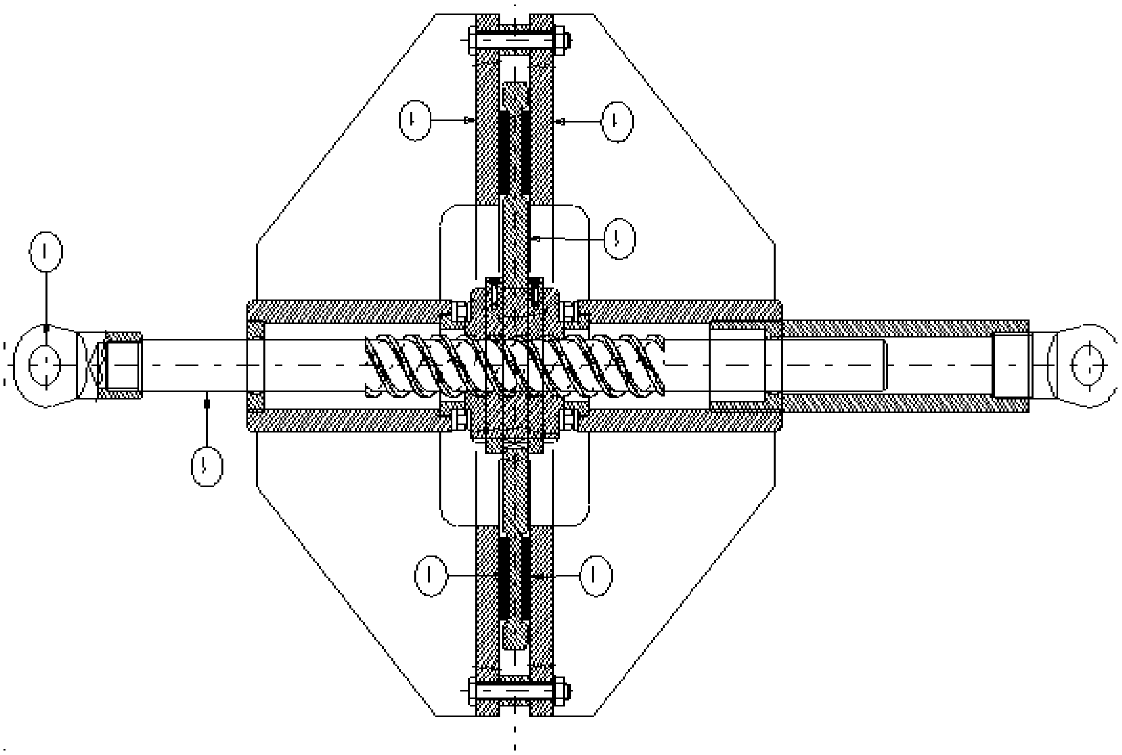

Figure 2: Structure of a rotating, passive DECS:

1 = spherical hinges to connect the device to the structure;
2 = permanent magnets;
3 = rotating disk developing losses;
4 = fixed support plates for permanent magnets;
5 = endless screw.

The manufactured rotating device is shown in the figure 3. the device is suited to operate when a relative linear motion occurs between the two spherical hinges that are connected to two parts of a structure in relative motion or to the test machine as in the figure 3.

Figure 3: Rotating DECS

The rotating disk (made of a conductive, not magnetic material and characterised by a low inertia) is driven by the endless screw: this disk, crossed by the magnetic field, represents the induced electric circuit, in which all the power loss is developed. Different materials have been considered for the disk in order to optimise the device response taking into account also the thermal phenomena occurring during and after the seismic event.

The device internal temperature in the active area (disk active belt and magnets belt) is a critical design aspect: too high disk temperatures could damage the disk itself (plastic thermal deformations, eventually fusion of the active belt material) and could transfer high temperatures also to the magnets that, subjected to demagnetising induced currents, could be damaged.

The design of the illustrated device has been performed in order to obtain a dissipation level comparable with standard viscous dampers; the endless screw pitch has been calibrated in order to minimise the friction between it and the rotating part but also to guarantee an adequate rotating speed of the disk. The permanent magnets location has been studied in order to obtain a suitable relative velocity between them and the rotating surface.

As for the linear device different tests have been performed to verify the device response cycle.
The first test at very low velocity (lower than 0.01 mm/sec) allows to calculate the device friction approximately equal to 20 kN. The high speed tests have been performed using sinusoidal and triangular excitations with a frequency range between 1/200 and 2 Hz and amplitude from ± 10mm up
to ± 80 mm.

The comparison between measured and theoretical response cycle is shown in the figure 4.

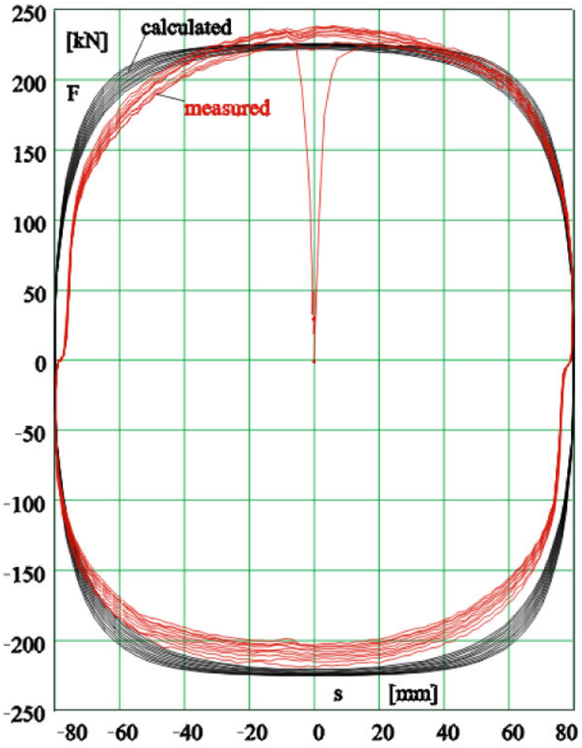

Figure 4: Comparison between the theoretical and measured response cycle of the rotating DECS

The measured device response is very close to the one calculated in the design; the measured maximum reaction force is about 225 kN (the maximum force assumed in the design of the mechanical components was 250 kN).

The differences in the response cycles around the level of force equal to zero, that corresponds to the displacement sign change, are due to the fact that the theoretical model does not take into account the endless screw transmission system. When the displacement changes its sign the tolerances on the thread and the elastic deformations of the mechanical components generate a gap in the response cycle. The disk rotation (consequently electro inductive dissipation) starts only when all the transmission system gap (approximately 3 mm) has been compensated and this fact explains the little shift of the measured response cycles.

One of the main concern in the device design was the influence of the temperature in the device functioning. The cycles shown in the figure 3 represent a test with 10 cycles and no significant changes in the device response has been noted. The temperature of the rotating disk external surface, measured, at the end of the test is approximately of 70 Celsius degree, while it is reasonable to suppose that the surface directly close to the device active area (permanent magnets surface) has been subjected to an higher temperature without any damage to the permanent magnets.

After few hours, with the device completely cooled, some tests were repeated with no significant changes in the response cycles; at the end of all the tests the device has been subjected to many excitations certainly more than the one expected in a real application without any damage or response degradation.

The promising results obtained by the tested prototype suggested the authors to start a preliminary design of rotating DECS with force and displacement capacity suitable for installation on real structures in order to offer an alternative to the viscous dampers.

3. Feasibility study

Recently for an important project of a bridge in Greece a feasibility study and a preliminary design of rotating DECS devices has been performed. The general scheme of the investigated devices is the same of the one shown in the figure 2.
The rotating devices has been designed for force level from 3000 kN to 5000 kN and displacement over 1 meter. An example of the studied device is shown in the figure 5.

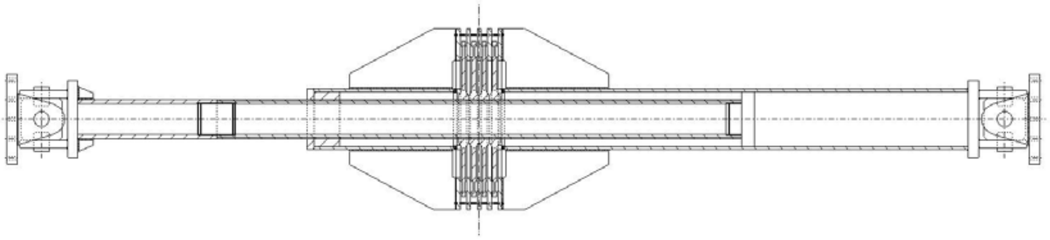

Figure 5: Designed rotating DECS with force capacity of 5000 kN.

The designed DECS is suitable for the installation on the structure, has a dissipating cycle comparable with the one obtained by viscous dampers and does not require relevant maintenance.
The expected costs are very promising and are comparable with the ones of the viscous dampers.

4. Future developments

The research project on electro--inductive dissipators is still in progress and the developments will be the design of semi--active dissipators where the dissipation (i.e. the damping of a structural system equipped by electro--inductive device) can be adjusted and adapted to optimal values obtained by a structure monitoring and control tools. Once semi--active devices have been designed and tested, also active electro inductive devices will be designed and tested.

The experimental activity will include and also shacking table test on a structure equipped by passive electro--inductive dissipators.

In parallel to the device design and testing in the research project the possible application of the electro inductive devices on civil structures is under investigation according to the Eurocode 8 regarding the structure design in seismic areas.

One of the most significant problem of the actual codes is, in particular, the definition of the anti seismic devices response properties at different seismic signal levels (frequent and destructive earthquakes) and the safety coefficients to be applied. A finite element model of a structure equipped by an electro--inductive dissipators has been prepared and some non linear dynamic analyses have been performed to evaluate suitable damping values (obtained by electro--inductive dissipators) and show how a semi--active dissipator device response can be adapted to different seismic signal levels respecting the Eurocode requirements and its safety coefficients.

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