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DEVELOPMENT OF A NEW SEMI-ACTIVE FRICTION DAMPER USING PIEZOELECTRIC TECHNOLOGY FOR THE ANTI-SEISMIC CONTROL OF CIVIL STRUCTURES

SUMMARY

This work presents a new semi-active friction damper, based on the piezoelectric technology, for the anti-seismic control of a civil structure. The device has been conceived and designed at D.I.A.S. (Department of Aerospace Engineering) of University Federico II of Naples. It belongs to the family of the semi-active technologies of structural control for a civil structure. Damper is based on an external cylinder and an internal hollow piston that slips inside the cylinder. Device presents an original conceptual lay-out, developed at D.I.A.S and it is independent by any scheme, available in literature.

***Keywords**: semiactive, friction, damper, piezoelectric*

NOWY SEMIAKTYWNY TŁUMIK PIEZOELEKTRYCZNY
DO TŁUMIENIA DRGAŃ SEJSMICZNYCH BUDOWLI

W pracy przedstawiono nowy semiaktywny tłumik cierny wykorzystujący elementy piezoelektryczne. Tłumik jest przeznaczony do zabezpieczenia budowli przed zjawiskami sejsmicznymi. Konstrukcja tłumika powstała w D.I.A.S na Uniwersytecie Federico II w Neapolu. Tłumik składa się z zewnętrznego cylindra i specjalnie skonstruowanego tłoka. Urządzenie zawiera całkowicie oryginalną koncepcję wykorzystania elementów piezoelektrycznych rozwijaną w D.I.A.S. Różni się ona od wcześniej opublikowanych rozwiązań w tej dziedzinie.

***Słowa kluczowe**: układy semiaktywne, tarcie, tłumienie, piezoelektryczność*

1. INTRODUCTION

The control of structures, subjected to seismic excitation, is a great challenge for the civil engineering field. The classical approach for the mitigation of seismic hazard, consists in a design of structures with a sufficient capacity of strength. This approach, is referred to as "strength based design", requires the resistance of individual structural elements to be greater than the demand associated with extreme loading. In this way, after the structure is designed, properties of stiffness are derived and used to check the various serviceability constraints for example, elastic behaviour (Condor 2002).

Recent developments have limited the importance and effectiveness of the "strength based design". In fact, the construction of structures with more flexibility (longer span horizontal structures and taller buildings) leads to more structural motion under service loadings, thus giving emphasising serviceability. New types of buildings as semiconductor factories have more severe design constraints on motion than the typical civil structure. Moreover, the experience of recent earthquakes has proven that costs, needed to repair structural damage due to inelastic deformation, were greater than expected; this represented a valid motivation to decrease the reliance on inelastic deformation and on the contrary to control the structural response with other types of energy dissipation and absorption mechanisms.New requirements and recent project trends have contributed to promote a new philosophy of design, referred as "motion based structural design". This design approach gives its attention to motion compliance with design requirements such as restrictions on displacement and acceleration, and seeks for the optimal deployment of material stiffness and motion control devices to achieve these design targets as well as to satisfy strength constraints. Structural motion control is the technology enabling motion based design (Condor 2002).

Structural control devices are divided into three great families: 1. passive, 2.active, and 3. semiactive control systems. A definition of these three categories is detailed in the work of Symans and Constantinou (1999). Both passive and active control systems have been growing in acceptance and may preclude the necessity of allowing for inelastic deformations in the structural system. A compromise between passive and active control systems are semi-active control systems. These maintain the reliability of passive control systems while taking advantage of tunability parameter characteristics typical of an active control system (Symans and Constantinou 1999).

The present work is focused on semiactive control systems, this category includes devices like variable stiffness control devices, electrorheological dampers, magnetorheological dampers, variable friction control devices, and fluid viscous dampers (Symans and Constantinou 1999; Soong and Spencer 2002). Among these types of semiactive devices, the activity proposed in the next pages regards

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a variable friction device. A semi-active friction damper consists of two bodies which slide with respect to each other, subjected to a controllable contact force, generating a dissipative force proportional to the contact force and to the coefficient of friction between surfaces.

It is possible to generate the contact clamping force with different systems of actuation. Pandya describes an experimental test program relative to semi-active friction dampers, installed along the diagonal bracing of each storey of a small-scale four-story structure, mounted on a vibration table. This semi-active damper consists of a sliding friction interface on which an adjustable clamping force is supplied through a pneumatic actuator (Pandya 1996). An experimental isolation system, including semi-active friction controllable sliding bearings, is described by Feng (1993), Feng *et al.* (1993) and Feng and Fujii (1992). In these cases, the clamping forces are produced by fluid presssure.

Today, piezoelectric technology for the generation of clamping force appears a promising choice. The first studies were carried out by Chen and Chen (2000, 2002, 2004), Chen *et al* (2004). The clamping force in a Piezoelectric Friction Damper (PFD) is regulated by piezoelectric stack actuators, which can quickly and accurately respond to a driven command such as a voltage signal. In addition, piezoelectric actuators are effective over a wide frequency band, reliable and compact in design, as demanded in civil engineering applications (Chen and Chen 2004). Durmaz *et al.* (2003) have developed a prototype of friction damper which gives a significantly higher control force with low power consumption. Chen and Chen (2004) in their work evaluated experimentally the performance of the semi-active control strategy and of a fabricated PFD. They conducted a series of shake table tests on a quarter-scale, three-storey building model controlled by PFD.

In this paper it is proposed a preliminary design and structural sizing of a new semiactive friction damper with piezoelectric actuation. The device is based on a conceptual layout, developed in the Department of Aerospace Engineering of University Federico II of Naples. The scheme proposed has been oriented to a compact and easy allocation of the piezoelectric actuator and it is original because it is different from any other available in literature.

2. DEFINITION OF THE TARGETS FOR THE SIZING OF THE SEMIACTIVE FRICTION DAMPER

In order to size the semiactive friction damper with piezoelectric actuation and subsequently to design the device, a configuration of a civil structure and a reference earthquake were assumed.

The structure is composed by a two storey steel frame that reproduces a real structure in scale 1:2 (Pecora *et al.* 2008). Frame pillars were realized using HEA100 beams while UPN100 were used as floor beams. Each storey has a height of 2 m and is characterized by a rectangular 2.4 × 3 m plant shape (Fig. 1). The structure under consideration is also provided with lateral reinforced elements represented by X-braced angular bars with an "L" section shape and dimensions 30 × 50 × 5 mm. The frame is physically located in the center "Casaccia" of E.N.E.A (Ente Nazionale Energie Alternative). In the final configuration of this steel frame, each floor is composed of a zig-zag steel sheet with a slab in reinforced concrete. Concrete blocks are disposed on each floor to obtain inertial features of Table 1. The total frame has been modeled in software Patran/Nastran. By means of correlation of theoretical modes parameters to the ones coming from ground vibration tests (Pecora *et al.* 2008).

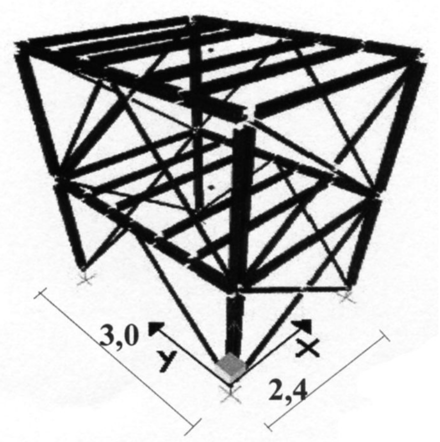

Fig. 1. Digital model of the steel frame

Table 1

Inertial properties of each floor of the steel frame

No. of floor	Mass M (kg)	Polar Inertia (kg·m^2)
First Floor	5032	6190
Second Floor	4099	6151

Together with the civil structure, a seismic excitation was selected to define the reference configuration. The seismic signal is unidirectional and is applied in the Y direction. The signal considered belongs to the first seismic class with a Peak Ground Acceleration (P.G.A.) of 3,2 m/s^2 (Fig. 2).

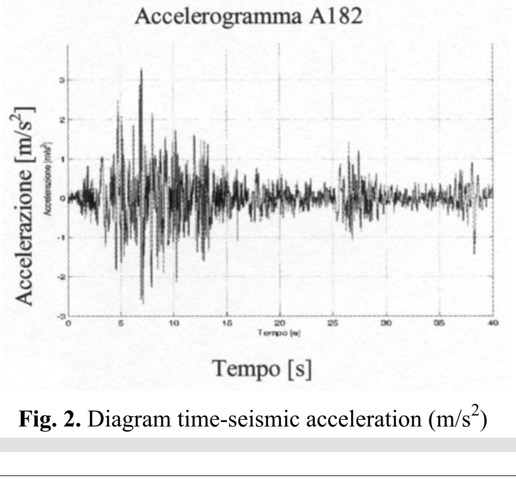

Fig. 2. Diagram time-seismic acceleration (m/s^2)

A software of simulation, denominated EarthSim has been specifically implemented by the authors in Matlab/Simulink program language. The developed software enables us to simulate the vibration response in terms of acceleration, velocities, and the displacements of the storey when the steel frame is subjected to seismic excitation, applied at the base of the structure. Two specific modules were dedicated respectively to the simulation of the piezo-actuated friction damper and to the control law (Chen and Chen 2004). In general, the use of EarthSim enables us also to compare different solutions of structural control as well as to define the performance requirements of a device (after its proper modelling) and to optimize the parameters related to control logic. Besides, for buildings with many storeys, the algorithm of simulation can be used to define the best location of devices in the structure.

In the case of the particular steel frame and seismic excitation, considered for sizing the semiactive piezoelectric friction damper, each floor of the frame has been modeled with four nodes, located at the corners of the floor and each node having six degrees of freedom, for a total number of 48 degrees of liberty. Simulations using a semiactive device deactivated and with damper activated were carried out. In the last case, several combinations of values for the parameters of the control logic, preload and maximum control force of friction device were considered. In this manner it has been identified a configuration that in the controlled case (devices activated) provides a reduction of the floor's acceleration of 22% with respect to the uncontrolled case and a reduction of 50% of the floor's displacement.

This configuration is identified by a preload for the device (force generated a piezo of 8800 N, by a contribute of a maximum control force, generated by a piezo of 4200 N, for a total of 13000 N, a value of 15 Hz for the working frequency of the control algorithm and values of 70 000 and 7000 respectively, for the non dimensional "e" and "g" parameters of the control algorithm (concerning the control logic, the reader is deferred to (Chen and Chen 2004)).

3. DESIGN OF THE SEMIACTIVE FRICTION DAMPER AND SPECIFICATIONS OF THE TESTED DEVICE

After the definition of the target relative to preload and maximum force as described in the previous paragraph, the design phase was carried out. C.A.D. 3D Proengineer was used to draw the digital mockup of single parts of the device and for its assembly (Figs. 3 and 4). Moreover, accurate structural verifications were addressed by using Ansys code (Fig. 5). The definition of a correct assembly and disassembly sequence was identified. After a definition of tolerances for each piece, the prototype was manufactured (Fig. 6).

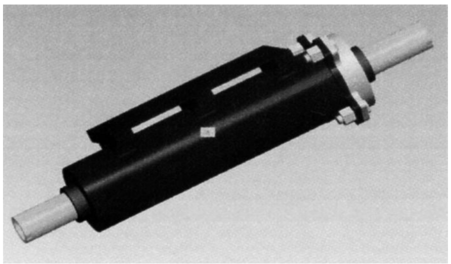

Fig. 3. Digital mockup of the damper

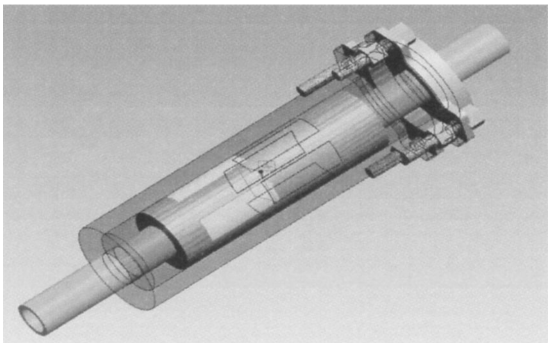

Fig. 4. Digital mockup of the damper with cylinder transparent

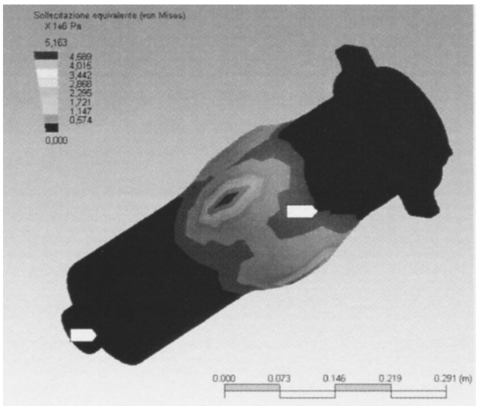

Fig. 5. F.E.M. Analysis – Ansys model

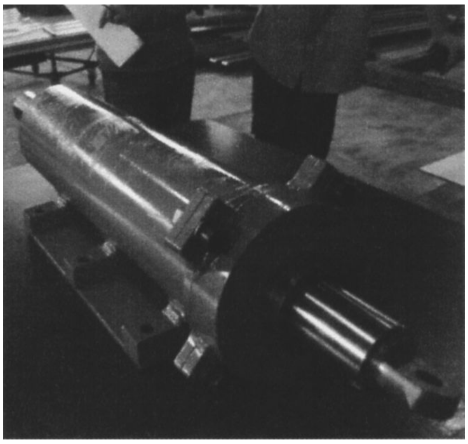

Fig. 6. Physical model of the damper

The device was designed according to an original conceptual design, that provides for a compact and easy allocation of a piezo actuator, embedded inside the piston of the damper. This scheme allows us to generate (from the piezoelectric actuator) a clamping force of four pads of friction material. The piston (visible in Fig. 4) slip inside the cylinder, when there is relative movement between the ground floor and the first storey and/or between the first and the second storey. The relative movement is generated from the seismic excitation. Piston and two rods (the piston is linked to each rod through threads) slips in the cylinder and a friction force is generated by the four pads of friction material. The cylinder can be linked to a beam of the frame or to the test machine (for bench tests) through a steel plate, (Figs. 3 or 6) and six bolts.

For this application has been chosen the piezo actuator Pst/1000/16/150 VS25, produced by Piezomechanik Gmbh, The same producer has supplied an amplifier PVR 1000/1 to drive the actuator with an high voltage signal. The selected piezo presents a maximum stroke of 150 μm and a generated maximum force of 10 000 N in correspondence with a feeding tension of 1000 V.

A critical point for the piezoelectrict actuator is the protection from tensile forces, from a bending torque at the tip and from the torsion loads. The chain of parts inside the piston, constituting the scheme in which is implemented the piezo, allows to avoid these stresses with some solutions specifically studied for this application. In fact the disposition of the pieces of the chain and their links are intrinsically unable to apply a tensile force to the piezoelectric device. In order to avoid bending or torque, a half sphere is inserted at the tip of the piezo.

By the typical characteristic curves Force-Displacement, parameterised in the function of the electric tension provided by the piezoelectric actuator control system, an increase in length of the piezo corresponds to a decrease in its capacity to generate a force, for this reason it is important to avoid the displacement of the piezoelectric tip. About this point the studied mechanism is made to recover in the assembly phase mechanical clearance and at the same time to give the desired preload to the semiactive friction damper. Moreover, all pieces of the chain are designed and manufactured to guarantee reduced deformations under the load of the piezo, which limits its extension and consequently the decrease of its performance. The decrease resulting by an extension is calculated by the following equation:

$$\begin{aligned} F_{\text{Max Real}} &= F_{\text{Max Extension Zero}} - (\text{PiezoStif} \times \text{Exst}) = \\ &= 10\,000\text{ N} - (90\text{ N}/\mu\text{m} \times 60\ \mu\text{m}) = 4600\text{ N} \end{aligned} \qquad (1)$$

where:

$F_{\text{Max Real}}$ – max force that the piezo can give after its extension,

$F_{\text{Max Extension Zero}}$ – max force that the piezo can give for a null extension (Blocking Force),

PiezoStiff – Stiffness of the Piezo actuator,

Exst – Extension of the Piezo = Total deformation of the chain.

After an iterative procedure of simulation with the Ansys about the deformation of parts of the damper, a max total deformation of the chain in contact with the piezo has been estimated in 60 μm, value reported in the eq. (1). In this manner, the max force attended by the piezo in the installation inside piston is 4600 N.

A friction material, out of catalogue, specifically studied for this application, has been supplied by ItalianBrakes s.r.l., that declares a dynamic friction coefficient with respect to a steel surface equal to 0.4.

Features of the designed and realized damper are: total mass of 85 kg, cylinder length of 618 mm, a stroke of piston equal to ±65 mm. As regards to the damper expected performances are: maximum variable control force due to the piezo equal to 5244 and a maximum control force due to piezo and preload together of 14 840 N.

4. CONCLUSIONS

This work presents a new semi-active friction damper, based on piezoelectric technology, for the anti-seismic control of a civil structure. The device has been conceived and designed at D.I.A.S. (Department of Aerospace Engineering), University Federico II of Naples. A civil structural typology, constituted by a steel building model, has been chosen as reference to size the device together with a seismic excitation signal.

A Matlab-Simulink simulation program, named EarthSim, was implemented to simulate the behavior of the steel frame under the chosen seismic excitation. Cases with and without the activation of the piezoelectric friction device have been simulated and a reference configuration for the structural control system has been identified. The damper has been designed to fit the performance required by the Matlab/Simulink simulation. The damper is based on an original conceptual lay-out, developed at D.I.A.S, and it is independent of any scheme, available in literature.

A prevision of expected performances of the device has been developed. These performances will be tested in the next experimental campaign, conducted on the piezo actuator and after on the damper with an hydraulic test machine, available in the Department of Science and Technique of Constructions (D.I.S.T.), University Federico II of Naples.

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