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# Toward a paradigm for civil structural control

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**Abstract.** Structural control is a very broad field combining the areas of automatic control and structural engineering, with applications ranging from aerospace and mechanical engineering to building and civil infrastructure systems. In this paper, the focus is placed on civil engineering applications only. The goal is to address the issues concurring to form the scientific paradigm. As a resut, possible future directions of research into this field are identified.

**Keywords:** design; paradigm; research program; structural code; structural control

## 1. Introduction

Epistemology, as theorized by Carnap and Popper, characterized the philosophy of the scientific approaches in the 20th century. Actually, a theoretical divergence between the US school (following Carnap) and the UK school (following Popper) occurred in terms of the criteria for assessment of the status of science: the verification of enunciations and theories (Carnap 1967) versus the falsification processes (Popper 1997).

During the 1960s and 1970s both approaches were deeply revised. Kuhn theorized a development of science through two different stages; namely, the stage of building the consensus on a specific view (i.e., setting the standards for a specific science), and the stage where innovative concepts are gathered and solidified (Kuhn 1962). The term "paradigm" was coined to characterize the set of agreed positions upon which the consensus is based. These agreed upon positions are the results which form the handbook of a discipline, where the rules of approach are identified through the consensus of the scientific community. This consensus comes either from verification or from falsification.

For the field of structural control in particular, the associated disciplinary "paradigm" has not been completely characterized yet, hence there is a need for further work to define the paradigm and identify its properties. The crucial question for any scientific discipline (Fornero 2006), including the discipline of structural control, is: What is the ultimate goal?

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The spectrum covered by this article is narrowed to the field of civil engineering with the following specification: “the structural control strategy is targeted at counteracting impact or random excitations, such as earthquakes, wind, explosions, etc., while the most important problem of vibration mitigation in mechanical engineering consists in counteracting periodic or polyharmonic excitations ” (see Kolovsky (1999), among others).

Structural control in mechanical and aerospace engineering is a discipline using the same conceptual tool within different design constraints. Therefore, if it is true that a researcher must be up to date in all application areas, these design constraints make a significant difference. This is the reason for which civil and infrastructure applications have to be approached separately. One could say that the research area of interest is presupposing given disciplines as automatic control and structural control as requisites. Moreover, the framework of the civil engineering applications commonly involves large masses, long lifetimes, and the need for adequate safety and robustness.

In the late 1980s and in the 1990s, the above remarks were well known to the pioneers of active structural control applications to buildings, who adopted a top-down approach (Yao 1972, Soong 1988, Kobori 1996). During the same period, a bottom-up revolution occurred in the field of passive structural control. Mainly the transformation of civil structural design from a fully static conception to a time-variant performance-based design suggested that improved results can be achieved by adding special devices, such as base isolators and/or energy dissipation systems. It is difficult to say if the time concomitance of the developments in the two areas of active and passive structural control is incidental or due to the fact that the two aspects are strictly correlated (Housner *et al*. 1997).

Since progress is pursued to achieve economic goals and to improve the system performance, it should not be controversial to state that the achievements in the field of structural control were derived within a “techné” approach. Books (see Preumont (1997), Soong and Dargush (1997) among others) were written to build the paradigm and to justify the funding of applied research. The field of structural control at its current level of maturity is in need of developments in both theoretical knowledge ("episteme") and practical applications ("techné"), via research based on a set of reasonable hypotheses ("doxa").

The aim of this paper consists of assessing the readiness of the discipline paradigm based on both the challenges specific of civil structural control, and the stage of development currently reached by the different control solutions. It will be shown that, although such a paradigm is already well established for some narrow areas, a unified one for the whole discipline is still lacking. As an outcome, the main topics in need of further research are identified. Due to space limitations, among these topics only few examples are chosen from the literature in order to outline the path toward the paradigm creation. In the authors’ opinion, this work is helpful in setting the future directions of the research efforts in the considered field.

## 2. The role of passive control

Passive protective systems for civil engineering structures include both base isolation strategies and energy dissipation devices. The first ones (Martelli 2013) are targeted to the counteraction of the seismic excitation only by cutting off the energy transmission of the earthquake ground motion to the structure. The latter ones consist of devices added to the structure to produce a control force as they are driven by the motion of the structure itself. Their parameters are initially set by the designer to achieve the desired response reduction at given frequencies, so that they are suitable to counteract external excitations which affect few predominant modes corresponding to the identified frequency ranges. It is part of the designer objectives to verify that their performance does not compromise the structural response when excited at frequencies which fall out of the selected ranges. Hence, when dealing with passive control, the "techné" aspects, i.e., the foreseen applications in terms of the structural type and the loading nature, cannot be ignored in the definition of a paradigm via an epistemological approach. From the studies reported in literature during the last decade, the use of certain devices in conjunction with structural types emerged most often. Wind engineering adopts viscous damper and TMD (tuned mass damper) solutions (see Casciati and Giuliano (2009), Giuliano (2013)) for a discussion on the limitations). Human structure interaction is mainly addressed by proposing TMD schemes (Caetano *et al*. 2010). Transportation (railway and road) infrastructures prefer since long time (Patten *et al*. 1999) viscous damper devices. Base isolators are quite effective in seismic areas. In particular, low-rise buildings of 4 - 10 stores and buildings not too slender with a maximum of 20 stores can be conveniently managed by isolation schemes, which also apply to short/medium span bridges. Tall buildings and long span bridges have advantage from inserting energy dissipation devices. A combination of the two schemes could result inadequate: a too high damping affects the isolation filter at the frequencies of interest for the contents, such as the equipments, thus causing non-structural damage as the one reported in high-rise isolated building during the Tonoku earthquake. The limit damping value should be 20-25% (lead rubber bearings).When base-isolation is adopted, the structural system is built on a rather rigid plate supported by the isolators. Ignoring one of the following items (for instance, the one listed as number 5, as it occurred in the well know accident at the Akrotiri site in Santorini, (http://www.greeka.com/cyclades/santorini/news/news/238.htm) could come with devastating consequences

1) Low amplitude excitations must find adequate stiffness ;
2) The displacements are assumed to be limited in the design phase since the excitation is limited in a structural code framework, but the uncertainty on the seismic input, mainly when defined on the basis of PSHA (Probabilistic Seismic Hazard Analysis), may result very large;
3) The bi-directional response of some devices must be guaranteed; the vertical component is significant for friction pendulum isolators;
4) Thermal and ageing aspects (especially with reference to some materials) must be carefully considered;
5) Isolation may result critical on soft soils characterized by seismic events with energy in the low frequencies (as in the Italian region Emilia or in the Rumanian country).

The design specifications for base-isolation and passive damper systems have been officially established in the engineering communities. Nevertheless, the researchers working in this field, after three decades of studies, are still expected to devote their efforts toward one or more of the following tasks,

1) The realization of experimental facilities able to validate the results of virtual design;

2) The development of virtual laboratories accurate enough to demand that only few validation cases must be investigated at the more expensive experimental stage;

3) The study of multifunctional materials toward their deployment in components whose design is targeted to the specific application of structural control;

4) The implementation of robustness so that the device can act outside the performance conditions for which the structure is designed. Indeed, the design mainly relies on simplified assumptions.

Research actions are also needed in order to assess the deviation of the obtained results from the actual performance of the built facility under extreme conditions.

## 3. A paradigm for active structural control

### *3.1 Scientific consensus on the requirements*

When discussing active structural control applications in civil engineering (see Casciati *et al*. (2012)) for a recent state of the art), three additional components are required with respect to standard structural design: sensor(s), actuator(s) and controller(s), with the last one(s) implementing suitable control laws. A collocated control (see Preumont (1997) for the definition) avoids the spillover, but non-collocated schemes can also be pursued. Centralized control (i.e., one single controller) is an option, but decentralized control schemes are particularly favorable for large, complex structures.

The design of a structural control system is a trade-off between cost and performance criteria; the serviceability type criteria result from the design constraints, whereas sometime it is more difficult a full identification of the ultimate limit-states. The power required by the devices distinguishes active from semi-active control: in the first case, the forces are directly applied to the masses of the structural elements; in the second case, only secondary components are displaced.

As said, the paradigm is the set of statements on which the scientific community agrees. If one focuses on active control, as different from semi-active control, the conclusion is that currently its technical implementations are still difficult, despite the many attempts that state the contrary as outlined in Casciati *et al*. (2012). Indeed, to counteract non-stationary transients requires a time of counteraction comparable with the dynamics of the structural system. Such a requirement is not easily supported by the current architectural way of conceiving a structural system as a static scheme where the actuators, which should be ready to start, are kept in stand-by for most of the time. Actually, in this context, only a few active control solutions were shown to be suitable to practical implementations. Among these, one includes the active mass dampers on the top of tall buildings, and the devices able to modify the tension in the stayed-cables of long span bridges or tall antennas. However, there is no technology which guarantees a prompt switch-on of the actuators. Hence, a "techné" improvement is still needed in order to set the paradigm.

There are also other issues that limit the applications of active structural control solutions in civil engineering, A partial set is given in the following with the intent of identifying the needs for further research in this field:

a. The maintenance frequency of the control system parts is quite high as compared to the one of common civil engineering systems;

b. During the periods of time in which the control system is under maintenance or temporarily out of commission, the safety of the structural system must be guaranteed without relying on the control system performance. If this implies the need of a design which does not take advantage of the control system, the resulting global cost is economically inefficient;

c. The global robustness of the system should be investigated, but up to now there are no general formulations suitable to address this issue.

In Casciati *et al*. (2012), two case studies are identified as structural types of fully new conception particularly suitable to the deployment of innovative active control strategies. Namely, a project by NASA (Sherwood *et al*. 2010) aiming to the settlement of a lunar village for androids, and the 4-D architectural concept (Fisher 2010, Faravelli *et al*. 2011) which is currently leading to the realization of tall buildings with time-varying floor orientation. The common theme justifying the adoption of active structural control solutions consists of the fact that the androids in the first case, and the structure itself in the second case are actually machines which require a maintenance plan fully consistent with the one associated to the control system components (sensor unit, microcontroller, and actuator devices). It is worth noticing that an extreme evolution along this streamline is represented by the tenso-structure introduced by Skelton (see, for example, Skelton and de Oliveira 2010) mainly for aerospace applications.

An attempt to summarize the research progress that has already been made in the field of active control of civil structures is represented by list of the activities carried out toward the solution of problems that will facilitate the application when feasible:

1. Moving from analog to digital technology (Casciati and Chen 2011, 2012, Kon and Horowitz 2008);
2. Development of sensors with the desired resolution (Kon and Horowitz 2008, Dong and Chen 2010);
3. Development of non-hydraulic actuators, since hydraulic actuators failed to be activated during the Kobe earthquake (Casciati and Domaneschi 2007, Hiramoto *et al*. 2011);
4. Development of schemes of integrated design (Cimellaro *et al*. 2009);
5. Development of system identification methods which are consistent with the control applications (Lin *et al*. 2001);
6. Development of tools for model order reduction with adequate accuracy (Casciati and Faravelli 2013).

The research activities listed above need to be ready for implementation before the expected new revolutionary idea in structural control becomes available. In the next section, further details related to the topic listed as item n. 5 are discussed with reference to an on-line parameter estimation technique for tracking the evolving structural properties of a highly nonlinear hysteretic system. Such a technique is selected as an example of active control approach which is suitable to realistic structural applications.

### *3.2 Example: online parameters estimation technique for active control applications*

In the last two decades since the pioneering structure (Kobori 1990) where a full-scale building was actively controlled to mitigate its structural response under dynamic loads, it became clear that in realistic applications to control structural response under strong ground motion, it is necessary from energy requirements to either rely on passive control approaches, or if active control is to be used, then the control should be used as a last resort to prevent severe damage (see Irschik *et al*. 1998 and Schlacher *et al*. 1997 among others). This philosophy of utilizing active structural control to deal with significant nonlinear structural deformations necessitates the development of sophisticated, yet reliable, active control algorithms that can handle complex nonlinear phenomena such as hysteretic features that are widely encountered in the structural dynamics field.

With the above in mind, this sub-section of the paper is dedicated to discuss a state-of-the-art active control approach which is suitable for realistic structural control applications. The proposed strategy utilizes an on-line parameter estimation technique for tracking the evolving structural properties of highly nonlinear systems, and subsequently uses the tracking results to develop an efficient control algorithm which provides significant attenuation in the response of the controlled system under a variety of transient dynamic loads.

A generic nonlinear single-degree-of-freedom (SDOF) structural system is shown in Fig. 1.

For the nonlinear SDOF system shown in Fig. 1, the equation of motion can be expressed as

$$m\ddot{x}(t) + r(t) = f(t) \tag{1}$$

where $x(t)$ is the displacement of the mass $m$ ; $r(t)$ is the nonlinear restoring force; and $f(t)$ is the system's external excitation.

It is important to ensure that the representation of the nonlinear restoring force $r(t)$ is general enough to model a wide range of nonlinear structural systems. A very general representation of such a restoring force function can be provided as the solution of a nonlinear differential equation

$$\dot{r} = g(r, x, \dot{x}; \boldsymbol{\theta}^*) \tag{2}$$

In this equation the term $\boldsymbol{\theta}^*$ represents a vector of unknown parameters (such as stiffness, damping etc.), that will be estimated by the on-line parameter estimation scheme. Eq. (2) is used to represent a variety of highly nonlinear systems, such as systems with polynomial nonlinearities, or systems exhibiting hysteretic behavior.

In order to estimate vector $\boldsymbol{\theta}^*$ an adaptive parametric identification algorithm was first presented in (Chassiakos *et al*. 1995, Chassiakos *et al*. 1998). The methodology was further developed in (Smyth *et al*. 1999, Smyth *et al*. 2002), and its applicability was extended, so that the resulting algorithm can be used for multi-degree-of-freedom (MDOF) nonlinear systems. While the method in (Chassiakos *et al*. 1998) uses a fixed "learning rate", the algorithm in (Smyth *et al*. 2002) uses a variable adaptive gain and a "forgetting factor" to better weigh the error caused by time-varying parameter effects.

For the active control of the nonlinear system (1), a control input $u(t)$ is acting on the mass so that the system equation becomes

$$m\ddot{x}(t) + r(x(t), \dot{x}(t)) = f(t) + u(t) \tag{3}$$

where the control input $u(t)$ is a function of the system's displacement and velocity, and of an auxiliary signal $\hat{z}$ , which is defined in Appendix 1. Details of the on-line parameter estimation algorithm, examples of how Eq. (2) is used for the representation of hysteretic structural systems (Wen 1980, Vinogradov and Pivovarov 1986), results on the parameter estimation algorithm and control of a highly nonlinear hysteretic system are also presented in Appendix 1.

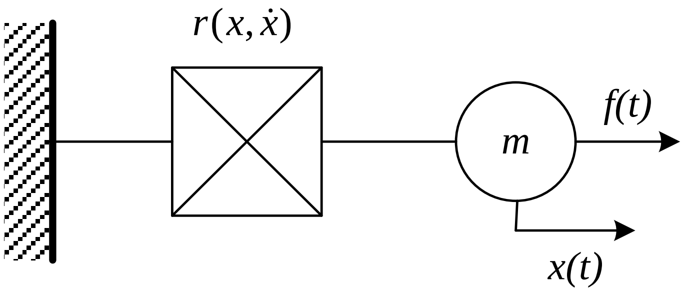



Fig. 1 Single degree of freedom system with nonlinear restoring force

## 4. The affordable semi-active control

Semi-active control devices have received a great deal of attention in recent years because they offer the adaptability of active control devices without requiring the associated large power sources. In fact, many of these devices can operate on battery power, which is critical during extreme events such as typhoons, tornados and earthquakes when the main power source to the structure may fail. According to presently accepted definitions, a semi-active control device is one that cannot increase the mechanical energy in the controlled system (i.e., including both the structure and the device), but has properties which can be dynamically varied to optimally reduce the response of a structural system. Therefore, in contrast to active control devices, semi-active control devices do not have the potential to destabilize the structural system (in a bounded input/bounded output framework) (Nishitani and Matsui 2013).

Analytical and experimental studies (Masri *et al.* 1989) have shown that appropriately implemented semi-active systems perform significantly better than passive devices and have the potential to achieve, or even surpass, the performance of fully active systems, thus allowing for the possibility of effective response reduction during a wide array of dynamic loading conditions.

Hence, he consistency between paradigm and implementations is achieved in the field of semi-active control, where the tuned mass dampers are assuming a dominant role. The main topics for current developments include (Casciati *et al.* 2006):

1) The introduction of new devices and their characterization;
2) The location of the devices across the structural systems;
3) The specific issues inherent to the implementation of a control law accounting for undesirable effects and time delay consequences.

Among the promising devices that have received attention in the recent past, those that can be classified as highly-nonlinear auxiliary mass dampers are herein selected as an example to recall how the problem is approached in the literature. Specifically, dampers that incorporate motion-limiting resilient "stops" to clip the relative motion between a primary system and its attached damper(s) are considered.

### *4.1 Example: adaptive nonlinear auxiliary-mass dampers*

Among the numerous types of damping devices that have been developed and applied for attenuating undesirable oscillations, the class of dampers that exploit “impact damping” phenomena for vibration reduction provides some useful features that are ideal for certain situations where ruggedness, reliability, and insensitivity to temperature extremes are a requirement for handling the encountered operating conditions. Members of this class of dampers include the single-particle impact damper, multi-unit/single-particle impact dampers, multi-particle impact dampers, arrays of particle dampers, and hybrid impact dampers that utilize a combination of momentum transfer devices with features characteristic of other classes of linear or nonlinear dampers (e.g., dynamic vibration neutralizers with motion-limiting stops). Some of the publications cited in the References section of the paper include analytical, computational, and experimental investigations of the class of damping devices that utilizes features of the impact damping mechanism (Araki *et al.* 1988, Panossian 1992, Saeki 2002, Wu *et al.* 2004, Fang and Tang 2006, Wong *et al.* 2009).

The long list of publications cited above, which covers a time span of several decades, attests to the broad interdisciplinary nature of the various issues involved in the modeling, analysis, simulation, design, and deployment of this family of dampers, as well as demonstrates the continuing effort by many investigators to address and resolve some of the many open questions that still await solution in regard to this highly nonlinear class of damping devices, when operating under arbitrary dynamic environments. The fact that the motion of even the simplest manifestation of this damper system (a single-particle/single-unit device) device under steady-state harmonic excitation can give rise to very complex chaotic motion, is one indication of the challenges encountered in trying to fully understand and analyze the physics involved in the three-dimensional operation of this family of dampers (even when a single particle is involved) under broadband, non-stationary, multi-component excitation, such as the one encountered in systems subjected to transient loads in aerospace, automotive, and civil structure applications.

While there are some appealing vibration-control features of the family of impact dampers as discussed above, there are also some accompanying undesirable characteristics; namely, the impulsive loads transmitted during the momentum exchange phase of the coupled system motion, and the attendant noise and potential local deformations accompanying the inelastic collisions among the system components. Furthermore, since the sensitivity of the primary system's response to the "tuning" of the optimum gap size in a single unit damper is quite dependent on the magnitude of the coefficient of restitution (Masri and Caughey 1966, Masri 1967) and other levels of inherent **(**dry friction) damping encountered during the damper operation, optimum design strategies have been investigated over the years. Nevertheless, there are still many unresolved issues needing study in order to investigate the performance of this class of devices under broadband excitation, stationary or not. An overview on the topic will be provided in the following, and some issues related to the adoption of hese dampers for applications involving the semi-active and passive structural control of civil infrastructures will be discussed.

### *4.1.1 Implementing a passive impact vibration damper device*

It was shown, both analytically and experimentally (Masri 1969) that, for a given total level of impact damper mass ratio, it is more advantageous to distribute the total particle mass in several units operating in parallel. The use of such an array of impact dampers leads to a reduction in the peak impulsive damping force, a considerable lessening of noise pollution, and a reduced sensitivity to the damper**(**s) gap size.

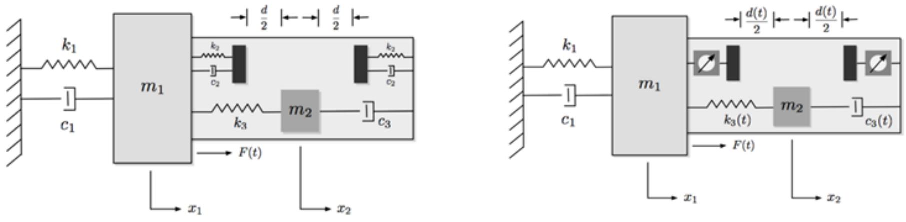
Furthermore, with the dramatic advancements in the field of material science focusing on material microstructure design (Christodoulou and Venables 2003), new classes of structural materials are being developed by targeting a specific set of functional properties. Such developments are paving the way for the production of composite materials that can have their micro-structure tailored to achieve specific functionalities (Vecchio 2005). It, thus, does not require a great leap of imagination to see the possibility, in the not too distant future, of composite materials with embedded micro-channels that provide the functionality of arrays of multi-unit particle dampers. Such composite materials can provide, in a distributed manner, the essential functionality of a granular material damper.

The need for efficient vibration damping over a broad frequency and amplitude range imposes severe requirements on the performance of the auxiliary mass dampers. One of the problems inherent in their application as practical dynamic vibration neutralizers consists of the excessive relative motion that the auxiliary mass undergoes at certain excitation frequencies, particularly if the mass ratio is small. The resulting excessive stress will cause early failure of the coupling spring.

Based on facts observed in model tests, Ormondroyed and Den Hartog proposed in 1928 the use of elastic "stops" to limit the excessive motion of the auxiliary mass relative to the main mass. The stops can be adjusted so as not to disturb the motion of the damper at the particular frequency for which it was tuned, while at other excitation frequencies they will limit the relative motion of the damper according to their adjusted clearance. Although Timoshenko (1928) and others expressed interest in this modified version of the dynamic vibration neutralizer, a limited number of analytical treatments of this topic are available in the literature (Masri 1972).

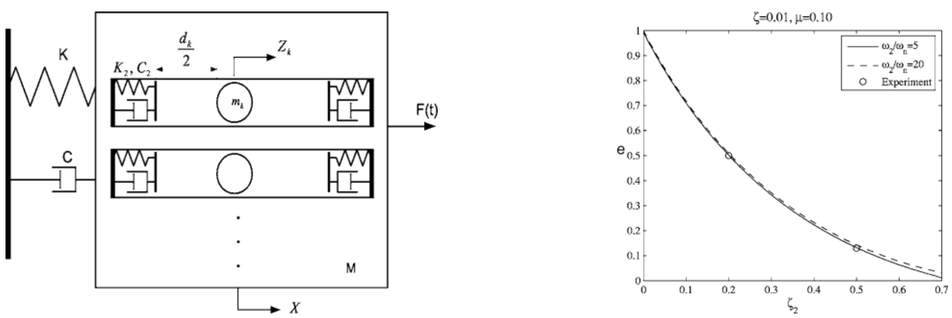
To clarify the complex behavior of a passive version of the device under discussion, a simplified two-degree-of-freedom model of a primary system equipped with a highly-nonlinear damper is discussed. The purely passive and semi-active versions are shown in Figs. 8(a) and 8(b), respectively. In addition to being coupled to the primary mass $m_1$ by means of a linear spring $k_3$ and a dashpot $c_3$, the auxiliary mass $m_2$ is constrained to oscillate with a clearance $d$ with respect to $m_1$. The amount of mechanical energy dissipated during the collision of $m_2$ with the "stiff" bumpers (when assumed to be infinitely stiff) is governed by the coefficient of restitution $e$, which varies in the [0,1] range, i.e., from the completely plastic case up to the completely elastic impact. Note that the nonlinearity in this problem involves the relative velocity as well as the relative displacement (Masri and Caughey 1966, Masri 1967).

Depending upon the choice of the parameters, the system in Fig. 2 can model various types of auxiliary mass dampers. For example, if $d/(F_0/k) >> 1$ and $c_3 = 0$, the system reduces to the well known dynamic vibration neutralizer; if $d/(F_0/k) >>1$, $k_3= 0$, and $c_3 \sim 0$, the system assumes the form of the Lanchester damper; and if the clearance $d$ is of the same order of magnitude as the size of $m_1$, and $c_3 = k_3= 0$, the system then represents the impact damper.




(a) (b)

Fig. 2 Schematic representation of a highly-nonlinear auxiliary mass damper coupled to the primary system: (a) purely passive version; and (b) semi-active model



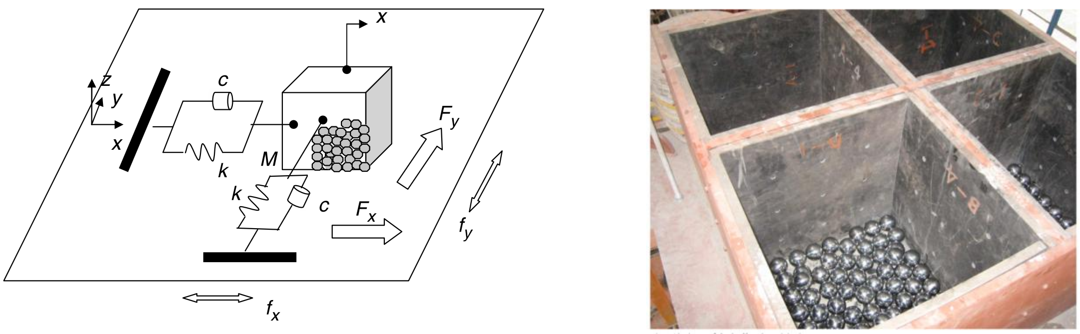

(a) (b)

Fig. 3 The multiple-units impact damper: (a) schematic representation; and (b) dependence of the coefficient of restitution, $e$, on the damping parameter $\zeta_2$ (Nayeri *et al*. 2007)

A simplified multi-unit version of the system under discussion is shown in Fig. 3(a). Its capability of providing a selected level of the coefficient of restitution, *e*, through a proper selection of the parameters $K_2$ and $C_2$, is shown in Fig. 3(b). It has been shown (both analytically and experimentally) that, with a proper choice of its parameters, the system under consideration alleviates some of the deficiencies inherent in other well-known dampers, and possesses superior response characteristics with respect to them (Masri 1972). Furthermore, it can be shown that a fully passive damping assembly can be designed to provide effective and robust damping performance, while simultaneously being relatively insensitive to variations in the spectral characteristics of wideband excitations, both the stationary and non stationary type (Nayeri *et al*. 2007).

By adjusting the number and design of the multi-unit dampers, the control system then approaches one acting as an assembly of particle dampers. Numerous applications of this class of nonlinear dampers have been performed in diverse fields such as aerospace, sports equipment, tire vibration, wind-induced vibration of slender structures, museum displays, electro-mechanical relays, etc. Some noteworthy studies of this class of dampers are reported in (Papalou and Masri 1998). Recently (Lu *et al*. 2010, Lu *et al*. 2011a, 2011b, Lu *et al*. 2011, 2012) reported on extensive analytical, computational, and experimental studies of particle dampers when they are used for the control of civil structures, in a single plane of motion, as well as in multi-component response situations. The simplified mathematical model in Fig. 4(a) is introduced to illustrate the state-of-the-art modeling approach typically adopted to study the particle dampers. The physical model used in a test structure that was investigated by (Lu 2012) at Tongji University in shown in Fig. 4(b). The multi-compartment particle damping system was used to control the dynamic response of the test structure under a variety of earthquake-like random excitations.

To illustrate typical vibration attenuation levels achieved by such dampers, the response time history at the top floor of the multistory building model tested at Tongji University (Lu *et al*. 2012) under random excitation is shown in Fig. 5, in which the left-hand-side column of plots (labelled (a)-1 and (b)-1) show the response measured at the second and first floor, respectively, without any structural control, and the right-hand-side column of plots (labelled (a)-2 and (b)-2) corresponds to the same response quantities when the system is provided with the particle damper.




(a) (b)

Fig. 4 Model of a particle damper: (a) schematic representation and (b) physical model used in (Lu 2012)

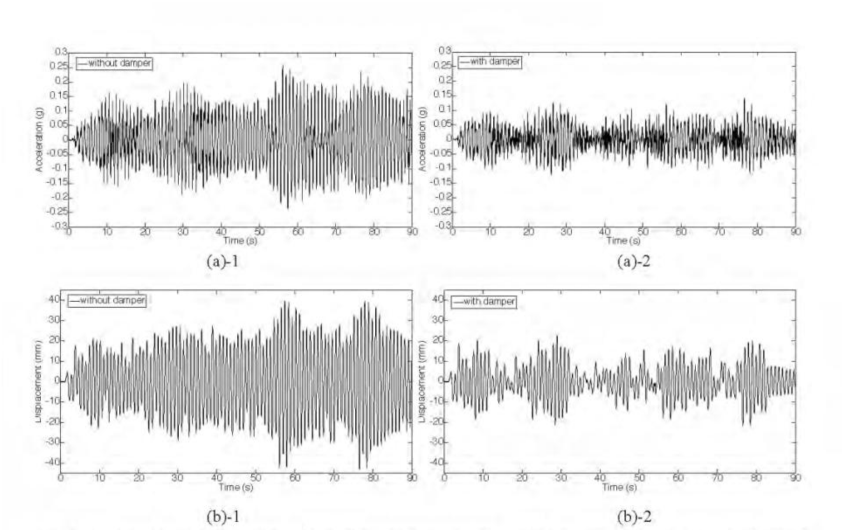



Fig. 5 Time-history plots of displacement and acceleration. (a)-1 and (b)-1: without control; (a)-2 and (b)-2: with particle dampers at the second and first floor, respectively, (Lu 2012)

#### *4.1.2 Implementing a semi-active vibration damper device*

As an illustrative example of the main attributes of a semi-active control device, consider an adaptive version of the classical passive impact damper discussed above.

Studies by Masri and Nishitani (2013) and Paulet-Crainiceanu *et al*. (2000) have shown that appropriately implemented semi-active systems for momentum-exchange devices (a semi-active impact damper) can perform significantly better than equivalent passive devices, and have the potential to achieve, or even surpass, the performance of fully active systems that utilize direct control forces that invoke pulse-control approaches for structural control (Timoshenko 1928, Masri *et al*. 1982), thus allowing for the capability of effective response reduction during a wide array of dynamic loading conditions.

The semi-active algorithm uses nonlinear auxiliary mass dampers with adjustable motion-limiting stops located at selected positions in a nonlinear system. A mathematical model of the system is not needed for implementing the global control algorithm. The degree of the primary structure's oscillations near each of the semi-active devices (i.e., only *loca*l measurements) determines an individual damper's actively controlled gap size and activation time. By using available control energy to adjust the damper critical parameters, instead of directly attenuating the motion of the primary system, a drastic reduction is achieved in the total amount of energy expended to reach a given level of vibration attenuation. In a related paper by Karyeaclis and Caughey (1987) the direct method of Lyapunov was used to establish that the response of the controlled nonlinear primary structure that is using the semi-active control strategy under discussion, is Lagrange stable.

An experimental test setup used to evaluate the effectiveness of such a semi-active control strategy is shown in Fig. 6. The normalized response of the primary system is shown in Fig. 7, where the normalized displacement and velocity are plotted together.

Fig. 6 Experimental test apparatus to implement semi-active impact damper approach

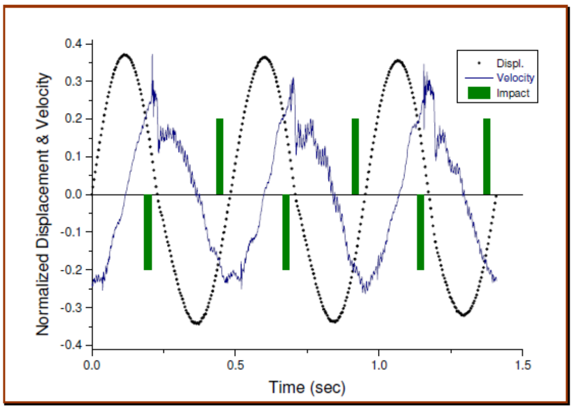



Fig. 7 Normalized displacement, velocity, and activation time of an experimental semi-active control device

Sample experimental measurements when the semi-active control device is undergoing free vibrations are shown in Fig. 8.

It can also be shown that, depending on the level of sophistication of the design, a significant improvement in performance can be achieved if an application allows the incorporation of adaptive stiffness characteristics of the dampers. With the availability of practical magneto-rheological (MR) dampers, and with approaches such as the one reported in Masri *et al.* (1989), the properties of the resilient stops, the nonlinearity threshold activation level (i.e., $d(t)$) as well as the linear coupling mechanism $k_3(t)$ and $c_3(t)$, can all be conveniently optimized through a suitable control algorithm to provide adaptive features (with negligible energy demands) to the structural control assembly under consideration.

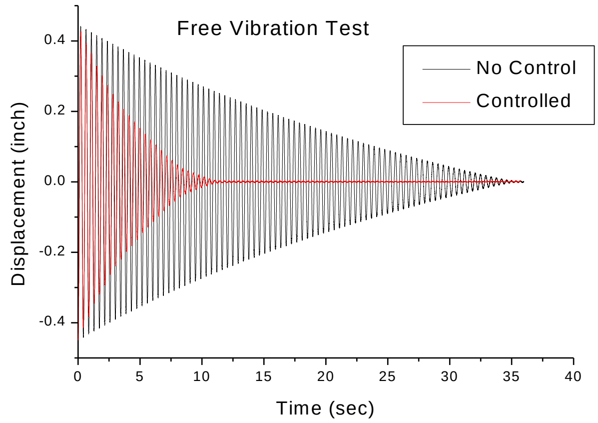



Fig. 8 Sample experimental results from a semi-active impact damper attached to a single-degree-of-freedom mechanical model

## 5. Foreseeable developments

### *5.1 Some steps along the techné (practical implementations)*

Given the current stage of development of the discipline which is discussed above with reference to different control strategies, what are the most likely implementations to which the research efforts could lead in the near future? In the following, an attempt to answer this question is made.

In the late 1990s, the structural control community (Housner *et al*. 1997) was addressing implementations such as the 1989 Kyobashi Seiwa building in Ginza (Kobori 1990), and the Nanjing tower instrumentally equipped by the University of Buffalo team (Cao *et al*. 1998). A recent review paper (Ikeda 2009) covers the most recent implementations in Japan, to which one should add applications on bridges worldwide and implementations in sky-scrapers in China.

Within the latter framework, Ni and Zhou (2010) explain how the mitigation control strategy is realized in the Canton tower (previously referred to as the Guangzhou New Television Tower). In particular, two control components are adopted: one for the tower and the other for the superimposed antenna. A hybrid vibration control system is devoted to the mitigation of the wind-induced vibrations of the main tower. It consists of two water tanks used as TMDs and coupled with two active mass dampers. The dampers work in collaboration to control the vibrations along the minor axis, whereas the vibrations along the major axis are controlled by the TMDs only. As the frequency of the first mode of the antenna mast is much higher than that of the main tower, the antenna mast is unable to benefit from the vibration control system of the main tower. Therefore, two further TMDs are installed to suppress the wind-induced vibrations of the antenna mast.

Another area of application is related to the structures mounting cables which can be easily tensioned/de-tensioned by actuators (Casciati and Ubertini 2008, Faravelli *et al*. 2010). This field of applications covers, for example, cable-stayed and suspension bridges, as well as the roofing of wide areas.

In the FEMA E-74 document (FEMA E-74 2011), attention is focused on the potential risk associated with nonstructural elements which could be involved in damage produced by environmental hazard. In particular, it is emphasized how “design of seismic bracing and anchorage for complex manufacturing systems is a significant engineering challenge and should be handled by design professionals with specific expertise in this area”.

### *5.2 Controlling the building skin*

The current drawback of the proposed structural control applications in Civil and Infrastructure Engineering is that the designer proceeds to append mechanical devices to structural systems conceived to have mass as their main property. A potential breakthrough comes from the innovations brought in building architecture by the requirements of light exposure and energy saving. For energy-minded architects and designers, a building’s façade has consistently been a critical and complex topic. It has the potential to capture, filter and integrate natural ventilation and daylight, manage solar heat, and provide visual and physical connections between indoor and outdoor environments. One of the challenges is to create a building skin that performs these functions without losing design appeal. The current approach to the problem is generally referred to as the realization of an “intelligent skin” (see, for example, the Plymouth School of Architecture or Faravelli *et al*. (2010). The skin of a building can be considered as the single greatest controller of a building’s interior environment in terms of light, heat and sound. The key characteristic of the intelligent skin consists of its ability to actively (which implies automatically) modify the energy flows through the building envelope by either the means of regulation, enhancement, attenuation, rejection, or entrapment. Thus, the intelligent skin is an active manipulator of the external elements with the ability to adjust itself autonomously to provide optimum internal comfort by self-regulated amendments to the building fabric, and the minimum use of energy. A possible solution sees the skin as composed of a series of horizontal louvers that are capable of increasing the distance between every two louvers by the angular rotation of two panels against each other. Cables embedded inside the louvers are responsible for their actuation.

Thus, a way to by-pass this temporary situation of stall is to enter into this “skin” revolution by adding to the required performance also structural goals, such as, for instance, a re-shaping of the surface under environment aggressions. Nowadays, it seems practically more feasible to pursue applications in wind engineering rather than increasing the structural resilience against earthquakes.

## 6. Conclusions

The task of producing a review paper on structural control, with special focus on Civil and Infrastructure Engineering, obliged the authors to answer the preliminary question if there exists an established “paradigm” for such a branch of Structural Engineering. In the attempt to answer this question, the topic was fathomed out, within the following pattern:

1) The paradigm for passive structural control can be stated and is consistent with feasible implementations;
2) The current paradigm for fully active structural control is inconsistent with the presently adopted design schemes so that adopting such a control solution is postponed until new

integrated architectures will be exploited;

3) Consistency between paradigm and implementations is achieved in the area of semi-active structural control, where tuned mass dampers are assuming a dominant role; this suggested the authors to recall a unified approach to the problem overlooking the fascinating perspective of disaggregated masses.

It is worth noticing that only a few full-scale case studies are mentioned in the literature, mainly operative in the area of wind engineering and human induced loading (Faravelli *et al*. 2010).

As a result of the critical points met along the paper, the following items should be privileged in the thematic scientific journals:

A) Integrated systems versus the early simple addition of a structural control system to a standard structural type;

B) A better delimitation of the fields of application of passive rather than active (or semi-active) control systems;

C) Dissemination of full scale successful implementations.

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## Appendix 1 – Estimation algorithm and simulation results for the procedure of sub-section 3.2

In this Appendix the parameter estimation and control schemes presented in sub-section 3.2 are applied to a SDOF nonlinear structure. As it will be seen from the simulations the parameter estimation scheme converges to the correct values within few periods, and the control inputs significantly reduce the effects of the external excitation.

For the development of the on-line estimation method of the unknown parameter vector $\boldsymbol{\theta}^*$ in (2), an auxiliary signal $z(t)$ is used, which contains combinations of the measured variables of the nonlinear system (1). Further we assume that the time derivative $\dot{z}(t)$ of this signal is expressible as a linear combination of the elements of the unknown vector $\boldsymbol{\theta}^*$ and of the measured variables, i.e.

$$\dot{z} = \boldsymbol{\theta}^{*T}\boldsymbol{\varphi} \tag{A.1}$$

where $\boldsymbol{\varphi}$ (the measurement vector) is a vector containing known functions of the measured variables. This assumption is not very restrictive, since polynomial structural nonlinearities as well as hysteretic nonlinearities can be written in this form as will be seen below.

Further processing requires that a low pass filter $\mathcal{F}$ is applied to each component of the vector $\boldsymbol{\varphi}$ in order to remove the measurement noise. The filter $\mathcal{F}$ is defined as $\mathcal{F} = 1/(s+\alpha)$ with $s$ denoting the Laplace variable and $\alpha$ a small positive constant. The resulting vector processed through the low pass filter is given by $\bar{\boldsymbol{\varphi}} = \mathcal{F}\boldsymbol{\varphi}$. Similarly the signal $z$ is processed through a filter $\mathcal{F}_1$ defined as $\mathcal{F}_1 = s/(s+\alpha)$ so that a filtered signal $\bar{z} = \mathcal{F}_1 z$ is created. Based on these definitions, after the filtering, Eq. (A.1) reads

$$\bar{z} = \boldsymbol{\theta}^{*T}\bar{\boldsymbol{\varphi}} \tag{A.2}$$

Let $\boldsymbol{\theta} = \boldsymbol{\theta}(t)$ be the estimate of $\boldsymbol{\theta}^*$ at time *t*. The estimate $\hat{z}$ of the filtered signal $\bar{z}$ at time *t* is then given by: $\hat{z} = \boldsymbol{\theta}^T\bar{\boldsymbol{\varphi}}$. The algorithm for the estimation of $\boldsymbol{\theta}^*$ uses the filtered measurement vector $\bar{\boldsymbol{\varphi}}$ and the error $(\bar{z} - \hat{z})$ between the signal $\bar{z}$ and its estimate $\hat{z}$, as shown in the following set of equations:

$$\left.\begin{array}{l}
\text{Adaptive law:} \quad \dot{\theta} = \mathbf{P}\varepsilon\bar{\boldsymbol{\varphi}} \\
\text{Estimation model:} \quad \hat{z} = \boldsymbol{\theta}^T\,\bar{\boldsymbol{\varphi}} \\
\text{Normalized estimation error:} \ \ \varepsilon = (\bar{z} - \hat{z}) / \lambda^2 \\
\dot{\mathbf{P}} = \begin{cases} \sigma\mathbf{P} - \mathbf{P}\dfrac{\bar{\boldsymbol{\varphi}}\,\bar{\boldsymbol{\varphi}}^T}{\lambda^2}\mathbf{P} & \text{if} \quad \|\mathbf{P}\| \le R_0 \\ 0 & \text{otherwise} \end{cases} \\
\quad \mathbf{P}(0) = \mathbf{P}_0 \\
\lambda^2 = 1 + \kappa\bar{\boldsymbol{\varphi}}\,\mathbf{P}\,\bar{\boldsymbol{\varphi}}^T \\
\text{where:} \quad \kappa > 0\ ;\ \sigma > 0\ ;\ R_0 > 0 \\
\qquad \mathbf{P}_0 \ \text{is symmetric and positive definite}
\end{array}\right\} \tag{A.3}$$

Examples of the application of the estimation algorithm to hysteretic structures are shown below. It is seen that the estimated values $\boldsymbol{\theta}(t)$ converge to true parameter values $\boldsymbol{\theta}^*$ within a few cycles of the system response, under sinusoidal or random excitations.

The nonlinear hysteretic restoring force $r(x(t), \dot{x}(t))$ of system (1) is be modeled by the Bouc-Wen model defined by the following differential equation (Wen 1980)

$$\dot{r} = (1/\eta)[A\dot{x} - \nu(\beta|\dot{x}|\,|r|^{n-1}\,r - \gamma\dot{x}|r|^n)] \tag{A.4}$$

where the parameters $\eta$, $A$, $\nu$, $\beta$, $\gamma$, and $n$ govern the shape of the hysteretic loop, which can assume quite different features, ranging from the ones typical of purely polynomial-like nonlinearities to those characterizing a fully elasto-plastic system.

The model of Eq. (A.4) was chosen for its ability to capture, in a continuous function, a range of shapes of hysteretic loops that resemble the properties of a wide class of nonlinear hysteretic systems (Vinogradov and Pivovarov 1986). The parametric modeling of the nonlinear element can be made even more flexible by incorporating additional terms into the model. For example, the Bouc-Wen model for the restoring force may be complemented by a linear damping parameter $c$ and a cubic term parameter $d$ as shown in equation (A.5)

$$r = kx + c\dot{x} + dx^3 - \int_0^t (1/\eta)[\nu(\beta|\dot{x}|\,|r|^{n-1}\,r - \gamma\dot{x}|r|^n)]\,\mathrm{d}t \tag{A.5}$$

The stiffness term $k$ in Eq. (A.5) takes the place of the $(1/\eta)A$ parameter cluster from Eq. (A.4), and hence it plays the same role.

Assuming that the system variables $\ddot{x}$, $r$ and $f$ are measurable, with $f$ denoting the system's external excitation, then $\dot{x}$ and $x$ can be obtained from $\ddot{x}$ by integration. Using the auxiliary signal $z = f - m\ddot{x}$ (which under this definition coincides with $r$), and after differentiation we obtain

$$\dot{z} = k\dot{x} + c\ddot{x} + d(3x^2\dot{x}) - (1/\eta)[\nu(\beta|\dot{x}||r|^{n-1}r - \gamma\dot{x}|r|^n)] \tag{A.6}$$

where the unknown parameters *k*,*c*,*d*, the clusters $\nu\beta(1/\eta)$, $\nu\gamma(1/\eta)$ and the exponent *n* represent the quantities to be identified by the on-line algorithm. It should be noted that the parameter *n* appears nonlinearly in Eq. (A.6), but this problem is circumvented by considering short series of terms with powers of $n = 0,1,2,\cdots$ and then identifying the corresponding coefficient clusters. With this in mind, Eq. (A.6) is rewritten as

$$\dot{z} = k\dot{x} + c\ddot{x} + d(3x^2\dot{x}) - (1/\eta)\sum_{n=1}^{N} a_n\nu(\beta|\dot{x}||r|^{n-1}r - \gamma\dot{x}|r|^n) \tag{A.7}$$

where $a_n$ are binary variables (0 or 1), and *N* is a user defined number that determines the maximum number of terms in the series. If one of the clusters is zero, then it can be concluded that the corresponding power term does not appear in the model of the system. By applying such a procedure, one finds that a model including the power terms up to *n* = 3 is more than adequate for most applications encountered in the applied mechanics field.

Now the assumption of Eq. (A.2) is satisfied, and the filtered signal $\bar{z}$ of Eq. (A.2) is written as $\bar{z} = \boldsymbol{\theta}^{*T}\bar{\boldsymbol{\varphi}}$, where $\boldsymbol{\theta}^*$ and $\boldsymbol{\varphi}$ are explicitly defined as

$$\boldsymbol{\theta}^* = [k, c, d, \ -(1/\eta)a_1\nu\beta, \ \ (1/\eta)a_1\nu\gamma, \ -(1/\eta)a_2\nu\beta, \ \ (1/\eta)a_2\nu\gamma, \cdots]^T \tag{A.8}$$

$$\boldsymbol{\varphi} = [\dot{x}, \ddot{x}, 3x^2\dot{x}, |\dot{x}|, \dot{x}|r|, |\dot{x}||r|, \dot{x}|r|^2, \cdots]^T \tag{A.9}$$

*A.1.1 Parameter estimation through a swept-sine excitation*

The response of the SDOF nonlinear system (1) to a swept-sine excitation force is simulated in this sub-section. The nonlinear restoring force is represented by Eq. (A.6), with the following parameter values: $k = 5,\ c = 0.5,\ d = 1,\ \eta = 1,\ \nu = 1,\ \beta = 0.5,\ \gamma = 0.5,\ n = 2$ .

For these values, the vector $\boldsymbol{\theta}^*$ is $\boldsymbol{\theta}^* = [k, c, d, -(1/\eta)a_1\nu\beta, (1/\eta)a_1\nu\gamma, -(1/\eta)a_2\nu\beta, (1/\eta)a_2\nu\gamma]^T$ $= [5, 0.5, 1, 0, 0, -0.5, 0.5]^T$

The swept sine excitation is given by: $f(t) = \sin((0.03t + 0.2)t)$ . The corresponding phase-plane plot of the restoring force vs. the response displacement is shown in Fig. A1. For this baseline scenario, the system's parameters are identified on-line, but no active control is employed.

A plot of the evolution of the parameter estimates is given in Fig. A2. The parameters start from zero initial values, and converge to their correct values $\boldsymbol{\theta}^* = [5, 0.5, 1, 0, 0, -0.5, 0.5]^T$ within the first 35 seconds of the swept sine excitation.

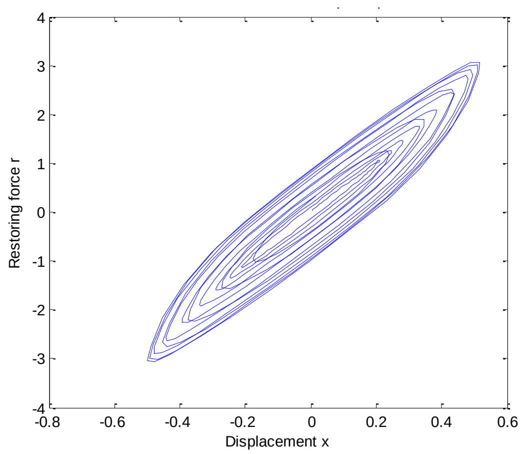


Fig. A1 Phase plane plot under swept-sine excitation

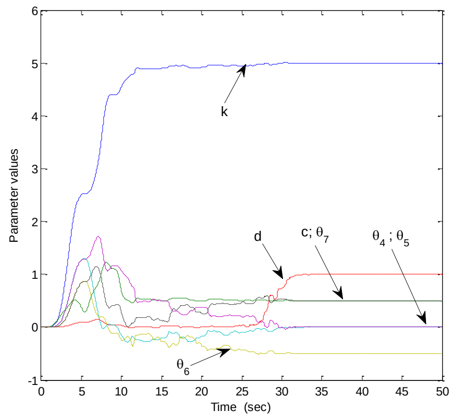


Fig. A2 Evolution of the estimate $\boldsymbol{\theta}$, under swept-sine excitation

### *A.1.2 Control of the response to a random excitation*

In this scenario a random excitation $f(t)$, simulating an earthquake input, is acting on the system. The input selected as random excitation is shown in Fig. A3. The evolution in time of the estimate of the parameter vector is plotted in Fig. A4. The parameters converge to the correct values within 15 seconds of the system response. In Fig. A5, the response of the system without control is compared to the response obtained with a control input of the form

$$u(t) = -K_1 x - K_2 \dot{x} - K_3 \int_0^t x(\tau)\, d\tau - K_4 (f - \hat{z}) \text{ , where } K_1 = 1,\ K_2 = 3,\ K_3 = 1.5,\ K_4 = 0.6 .$$

It is seen that the controller greatly reduces the effects of the random excitation on the system by decreasing the displacement amplitudes to less than half their uncontrolled values.

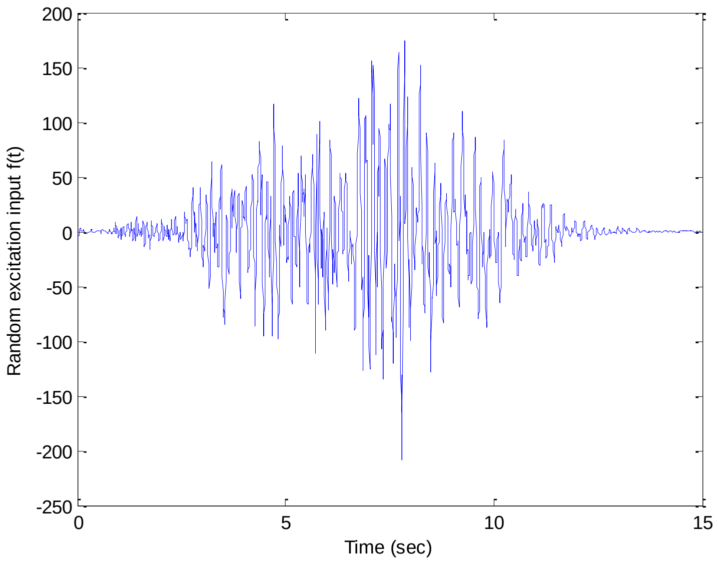


Fig. A3 Random excitation input

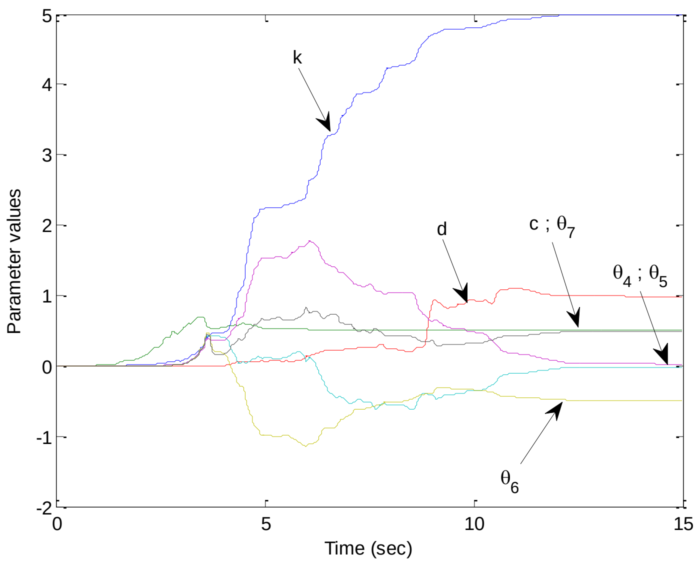


Fig. A4 Evolution of parameter vector $\boldsymbol{\theta}$ under random excitation input

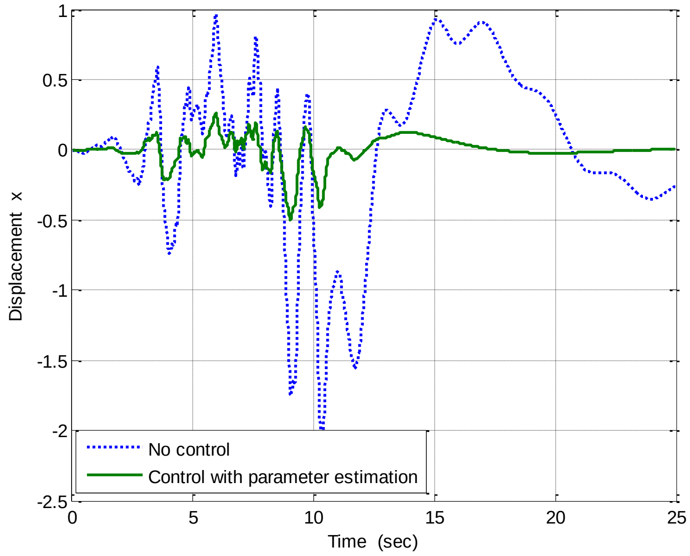


Fig. A5 Response to random excitation, with and without control