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ACTIVE CONTROL OF STRUCTURES IN EUROPEAN SEISMIC AREAS

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ABSTRACT

This paper gives a map of the research centers which are paying attention to the area of structural control in Europe (and, more generally, in the Mediterranean area). It also discusses the area of potential application of active structural control in the European context.

KEYWORDS

Active Control; Architectural Heritage; Hybrid Control; Rehabilitation Design; Strengthening; Seismic Vulnerability.

INTRODUCTION

According to the states of the art by Kobori (Kobori, 1988 and 1990), the development process of seismic response control consists of its initial philososphy and five subsequent steps as depicted in Figure 1. Thanks to some three-lateral workshops (Wen, 1992; Housner *et al.*, 1993), the concept (i.e the philosophy) was easily acquired by some European research laboratories and step I (= methods) development is comparable with the one in Japan and in the States as the rich literature testifies (Baratta *et al.*, 1995; Barbat *et al.*, 1995; Bourquin, 1995; Casciati and Faravelli, 1995; Faravelli and Yao, 1996; López-Almansa *et al.*, 1994a and 1994b ; Rodellar *et al.*, 1993). The next two steps (II = devices and III = full scale tests) are not matter for single research groups: they require an organization able to avoid duplicate and to concentrate the effort on goals of higher priority. This was accomplished by establishing the Association for Control of Structures (ACS) and its bulletin, the Journal of Structural Control.

ONGOING RESEARCH PROGRAMS

ACS is organizing the First European Conference on Structural Control in Barcelona, Spain, May 29 to 31, 1996 (Baratta and Rodellar, 1996). Seventyfive per cent of the summaries submitted to the organizing committee come from the Mediterranean area (which is of a seismic nature), while almost no interest was shown from Northern Europe.

Almost fifty per cent of these Mediterranean contributions deals with topics which are related to, but

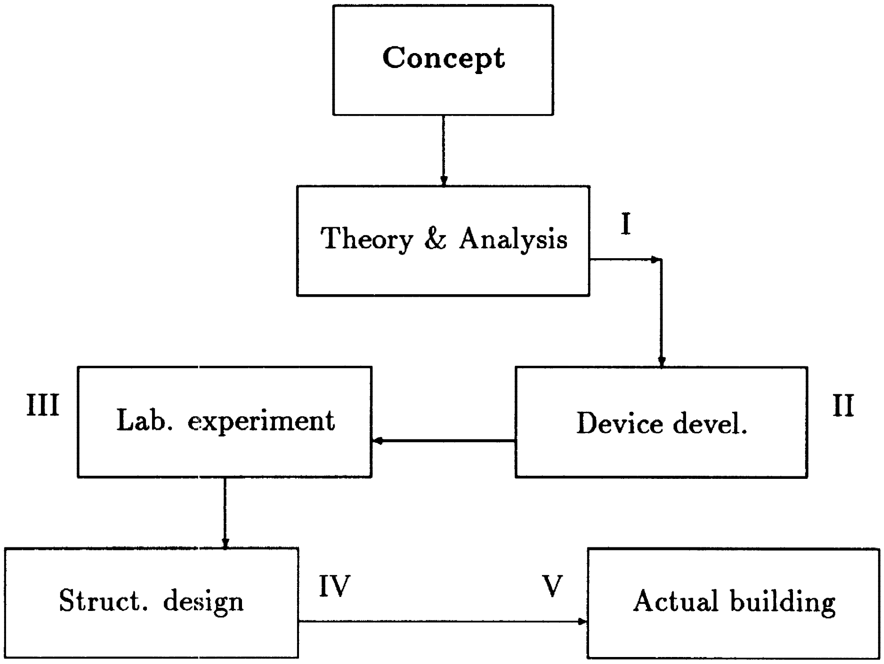

Figure 1: The way toward active control implementation (from (Kobori, 1990)).

are different from active control: i) structural identification, ii) smart materials, iii) vibration analysis, iv) passive control and v) base isolation. The remaining fifty per cent covers:

1. theoretical aspects of active control;
2. the operative implementation of active control schemes;
3. hybrid control solutions;
4. active control application to bridges;
5. reliability aspects of actively controlled systems.

The effort in progress in some North Africa and Middle East countries requires a special mention: at the Cairo University, in Egypt, attention is focused on actively joined structures; at the Teheran University, in Iran, alternative ways of expressing the control law are investigated; at the Tizi-Ouzou University, in Algeria, expert systems are investigated as a tool for structure pathology; at the Kuwait University, Kuwait, a mode localization approach is studied for both active and passive control purposes. Interest in active structural control was also shown in Eastern European countries as Russia, Poland, Romania and Czech Republic, but most of the contributions to the conference come from Austria, France, Italy, Spain and Portugal, while English contributions are much more oriented toward special material applications.

Large scale experiments are only conducted, on base isolated structures, by pseudo-dynamic simulation at the European Joint Research Center in Ispra. Shake-table tests are still at their planning stage at ENEA in Italy.

RESEARCH ACTIVITY IN SOME SPECIFIC LABORATORIES

Most of the research on active structural control in progress in Europe concentrate in three main laboratories (Baratta *et al*, 1995): the Technical University of Catalonia (UPC), Barcelona, Spain, the University of Naples (UNa), Italy and the University of Pavia (UPv), Italy. It is worth mentioning that even France has excellent centers in Lyon (Roberti *et al*, 1995) and Paris (Bourquin, 1995), but seismic applications are just one aspect of a wider interest in mechanical engineering and theoretical control, respectively.

Research on structural control at the UPC

In the Technical University of Catalonia the research activity on structural control began at the early 80's. Initial studies were numerical and dealt with applications of predictive control strategy for active control of building structures subject to earthquake loads (Rodellar and Barbat, 1985; Rodellar *et al.*, 1987). This control strategy was selected because it is appropriate for digital control loops (since it is formulated in discrete time) and can easily cope with time delays; this approach has been continuously used at the research carried out at the UPC. Later on, experiments on active control of a bridge model under traffic loads were carried out at Barcelona (Barbat *et al.*, 1988); actuators were electromagnetic devices.

In 1985, a theoretical and experimental study on active control of building structures was undertaken. Testing was performed at the State University of New York at Buffalo. Actuators were active cables hydraulically operated and predictive control was used for control signal generation. Results were published at the references (Rodellar *et al.*, 1989) and (López Almansa and Rodellar, 1989 and 1990). As a continuation, the same control strategy was considered for active control of seismically isolated buildings (Inaudi *et al.*, 1992). In 1989, the research effort concentrated on globally assessing the efficiency of predictive control strategy for active control of structures; a comprehensive parametric study was carried out (López Almansa *et al.*, 1994a and 1994b) and results were applied to Active Mass Dampers (Andrade *et al*, 1995).

Before 1990, the structure was represented by a linear and deterministic (certain) model and the excitation was considered as an unknown perturbation. In 1990, a theoretical study on stabilization of nonlinear uncertain systems using robust control (Lyapunov techniques) was initiated. Uncertainties were in the model of the structure as well as in the input. The stability criterion was related to "practical stability", i.e. the state of the system tends to a region including the origin. Results can be seen on the reference (Rodellar *et al.*, 1993). In the same context, an adaptive control strategy was applied to hybrid control (active control of nonlinear base isolated buildings) (Barbat *et al.*, 1995). In 1991, experiments on passive systems (Tuned Mass Dampers (TMD) using viscoelastic materials) were performed at the University of California at Berkeley (Inaudi *et al.*, 1993). Currently, testing on energy dissipation systems for building structures is in progress at Barcelona. Also, a study on the applicability of Large Scale Systems techniques (using overlapping decomposition) to active control of structures was started. Results were published in (Bakule *et al.*, 1992) and (Bakule and Rodellar, 1994a and 1994b).

The current research activity on structural control at the Technical University of Catalonia focuses on three topics; two on active control and one on passive control. Topics on active control are: optimal location of sensors and actuators and sliding mode control. Research on passive control deals with experimental assessment of the efficiency of energy dissipators. The problem of selecting the optimal position for actuators was tackled by the Virtual Distortion Method following a progressive collapse analogy (Holnicki-Szul *et al.*, 1993). For the optimal location of sensors a new approach that minimizes the condition number of a matrix is under investigation. Recently, research effort has focused on applications of Variable Structure Control (with sliding mode) to active control of structures.

Research on structural control at UNa

In the Department of *Scienza delle Costruzioni* of the University of Naples attention has been focused on what has been named step I in the introduction to this paper. The main purpose is to improve algorithms and to attenuate in this way the need for highly sophisticated hardware (or, from a reverse point of view, to improve the efficiency of the available devices). The interest in the topic of structural control is relatively recent and starts in 1991. Some states af the art were originally assembled with the purpose of disseminating the knowledge of the activity so far developped, and to promote cooperation with researchers in other fields (i.e. mechanical, aereonautical and so on). A considerable impact was given by the organization in the Naples' area of a three-lateral (with USA and Japan) workshop in the summer of '92 (Housner *et al.*, 1992) and since that date activity has grown up to some extent.

The initial steps were devoted to the problem of the delay in linear control action (Baratta 1992), showing how delay may be a serious obstacle to the performance of (linear) control especially for brief, intense disturbances like earthquakes. Unconditionally stable calibration of parameters in linear control has been developped by a formal setting of the design problem as the optimization of the "norm" of the solutor of the controlled motion equations, under the condition that the control forces remain bounded from above The procedure yields very significant attenuation of the structure strength at the price of comparatively small control actions. A numerical procedure to solve the equation of the controlled motion with or without delay was also formulated (Baratta *et al.*, 1994a). Optimization of the solutions in the case of delayed control has definitely proved that, after a given threshold, the best control action becomes uneffective, at least in the linear case. The applicability to MDOF systems has been widely tested. Compensation of the delay and pseudo-synchronization of the control action has been investigated by a stochastic predictive approach, that in some cases (e.g. for poorly damped structures) has proved to be satisfactory (Baratta *et al.*, 1994b).

Programs for future research aim at generalizing the norm approach to nonlinear systems, with the purpose to formulate optimal problems in the form allowing a definite bound on the structure strength and on the control force intensity. The widely tested procedure outlined in the above will be implemented for optimization of the design of the system, with reference to positioning of sensors and actuators and to the minimization of the weight and of the encumberment of additional masses.
The problem of optimal nonlinear control algorithm is approached with reference to a SDOF system, driven by a closed-loop control action. The control force is viewed at as a functional of the structure response, and an optimal identification of such functional is being attempted.
From the experimental point of view, an approach is being attempted to set up activities concerned with experimentation on scale-models. Programs for designing and realizing a joint experimental facility allowing to test and to implement algorithms and devices are in course of definition.

Research on structural control at UPv

In the Department of Structural Mechanics of the University of Pavia, the main investigators have been working for long time on problems of nonlinear structural dynemics, both in a deterministic and in a stochastic context (Casciati and Faravelli, 1991). Their attention was attracted by the developments in structural control after their participation in the International Workshop on Intelligent Structures held in Taipei in 1990 (Chong *et al.*, 1990). They contributed the organization of two USA-Italy-Japan three-lateral workshops in Italy (Wen, 1992; Housner *et al.*, 1993) and started to devote a significant part of their resources to the topic of structural control.

Initial studies were developed within an artificial intelligence framework and deal with applications of signal recognition via neural networks (Casciati *et al.*, 1993; Casciati and Faravelli, 1995). Neural networks were deeply investigated since their adoption permits one to avoid any model dependency and, hence, to perform implicit optimizations. Their potentiality in active structural control is discussed in (Faravelli and Venini, 1994) where some alternative schemes to apply back-propagation neural networks are proposed.
Active control systems must be capable of driving structures which behaves in a nonlinear manner and, in addition, should be able to accomodate noisy input measurements, uncertainty in system parameters values and possible changes to the system. One promising strategy that addresses most of these concerns is the application of fuzzy control (Faravelli and Yao, 1996). Within the ongoing research effort aiming at the realization of a preliminary feasibility study, attention was preliminarily focused on the implementation of a single-input single-output (SISO) fuzzy controller. Its practical application is immediately seen in the hybrid-control of a base-isolated structural system. The robustness of a

fuzzy controller is generally regarded as an intrinsic property. Its stability properties are still matter of discussion (Casciati, 1996).

The current research activity on structural control at the Department of Structural Mechanics of the University of Pavia focuses on four topics; three on the theoretical aspects of active control and one on the implementation of an experimental support. Research on an experimental basis is in cooperation with the University of Naples.

Topics on fuzzy active control are: optimal design of the controller and its adaptivity. The problem of selecting the membership functions and the rules of a fuzzy controller can be approached in an automatic way by using the so called neuro-fuzzy theory. Improvements to the approach already implemented in (Faravelli and Yao, 1996) are presently in progress. In paticular, focusing attention on deteriorating structures, adequate adaptive controller schemes are pursued and SAN/TAN (stage adaptive networks/trajectory adaptive networks) theory is a candidate to be exploited.

Studies still at an early stage are dealing with the problem of controlling chaos. The idea is to make operative a hysteretic base isolation within a chaotic range, so that its active control will require a limited amount of control energy (Battaini and Casciati, 1996).

A large effort is eventually devoted to the stability aspects of linear and nonlinear controllers. The problem is approached in terms of system reliability (Breitung and Faravelli, 1995).

COMMON OBJECTIVES

European designers are presently sceptic about the possibility of a direct application to earthquake engineering. The main reasons are:

- the low seismicity which characterizes large area of Southern European countries does not permit the constructor to concentrate investments in one area rather than another, as it is possible in California or in Japan;
- even if one decides to design a structure with an active control system, to maintain it operative along the wide periods of inactivity puts the global cost of the design out of the market.

One is therefore aiming at two special fields for steps IV (actual design) and V (construction) in a seismic context:

1. implementation of hybrid control systems, where the active device is a reliability bound for a base isolated system and/or for a construction with passive dampers;
2. implementation of semi-active systems, which use information from sensors in a closed-loop, but do not require a large amount of energy, so that they result reliable during strong earthquake;

For both the previous schemes, however, the problem is still the identification of a suitable class of buildings to be equipped. Their intrinsic value must be very high to justify the additional cost of active control devices. The idea is therefore to focus attention on the wide European architectural heritage. Studies of vulnerability were already developed and it is now the time to conceive adquate rehabilitation and strengthening designs. Hybrid and semiactive devices seem to be appropriate for this purpose, provided the necessary laboratory tests be preliminarly conducted. Special care will be devoted to the aged urban components of civil infrastructures. This fully justifies the title selected for the third International Civil Infrastructure System Symposium in its first European production (Fall of 1997): Rehabilitation and Renewal of Aging Infrastructures.

Hybrid control systems

If one installs high damping rubber bearings (HDRB), the base isolation shows a large hysteretic behaviour. The equations governing the dynamics of the supported structure are nonlinear and a nonlinear control problem arises. In addition, the sensor measurements are contaminated with noise and there is uncertainty in determining the structure parameters. A traditional controller is sensitive to this uncertainty and noise, especially in the case feedback is small (since the response is controlled). Under these conditions the controller is essentially reacting to noise, rather than to the structural response feedback. Attention must be focused on the components necessary for building an effective controller able to drive such a hybrid control scheme.

Semi-active systems

One of the main limitations of the active control systems for civil engineering structures is their low reliability since the actuators need a lot of energy to move the big and massive structures. This is specially relevant due to the low level of occurrence of earthquakes and their potential to disrupt normal sources of energy (electric power, pressure reservoirs, etc.). In order to skip these drawbacks, semi-active systems have been proposed trying to combine the advantages of the active systems (high performance) and of the passive ones (simplicity and reliability). Semi-active systems consist of closed control loops where the actuators are operated according to the continuously measured structural response but they cannot apply big control forces and so, do not have important energy requirements. In general, such systems are more efficient than the passive ones but less than the active ones. As an example, semi-active systems can include actuators that contain viscous dampers: the control action consists of closing or opening a valve in such a way that the damping properties of the actuator change.

Experimental activity

For starting an experimental activity, the basic idea is to develop a deep knowledge of the technical features of the control devices, in order to advance to step II (= devices) of the general research activity, as a preliminary to step III in a later future. A second line of experimental research is the application of the control technology in the testing of small scale models of large buildings. On both topics, a strict cooperation with ENEA and the Italian Seismic Bureau (SSN) is on the way to be activated, so that the deep background of the scientists working in these institutions be made available to the progress of active structural control.

CONCLUSIONS

Despite European designers are presently sceptic about the possibility of a direct application of active control theory to earthquake engineering, Europe offers its architectural heritage, in the form of monuments and infrastructures, as a promising field where special control devices could be implemented in the next future.

A strict cooperation with both the US and Japan panel would be suitable, convenient and, perhaps, necessary. The research grants from the European Union, however, are conceived, today, for promoting joint research within European countries (i.e. for making homogeneous the internal research spectrum), rather than for supporting world-wide cooperations.

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