

Structural Control for Wind and Earthquake Loads: NSF'S Coordinated Research Program

by

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1. INTRODUCTION

Civil engineering structures are commonly designed for their strength and stability. The structural systems are analyzed to calculate forces in various load-carrying elements such as beams, columns, etc. These elements are then proportioned such that they can withstand the calculated forces without overstressing or instability failures. Since elastically designed structures could be bulky and costly, they are allowed to yield, at least for extreme loads such as earthquakes. Such designs, therefore, admit the possibility of structural damage of the load carrying elements in an extreme event.

In the last two decades, there has been a growing interest to find ways to reduce or control the effect of the extreme events. The earthquake-induced effects on structures can be reduced either by filtering or absorbing the damaging energy transmitted to a structure. A significant amount of research has been done to develop base isolation methods that primarily filter out the damaging energy from reaching the superstructure. The base isolators increase the fundamental period of the system such that combined structure isolator systems shift into the lower response spectrum range.

The energy dissipaters or energy sinks, placed at suitable locations in structures, have also been used for reducing dynamic response. The energy dissipater that have been recently considered for earthquake applications are the viscous, viscoelastic, and friction dampers, and yielding devices that add damping and stiffness (ADAS) to the system. These devices absorb vibration energy that otherwise would have gone to deform and possibly damage the structural elements. These devices can be designed such that they are disposable. That is, an overly deformed or damaged energy dissipater can be replaced with new ones after a strong event, if considered necessary.

The aforementioned approaches are commonly referred to as passive control approaches, as the devices come into action only after the structure has responded to the external disturbance. The reliability and usefulness of these methods is now quite well established in structural engineering community. As such, these methods are being increasingly used in practice in buildings in seismically active regions. The National Science Foundation (NSF) has played a major role in the development of these passive control approaches; it has made it possible to bring these useful concepts to fruition and to implementation.

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stage by providing continuous funding to research projects dealing with this topic over the past twenty five years.

Along with the development of passive devices, the research community has also been exploring the development of the active control methods. In the active methods, the external forces are applied to control the response. The application of forces through tendons or other forms of actuators have been examined. When, where, and how much the forces should be applied is decided according to a suitable algorithm based on the measurements made on the response of the structure, and sometimes also on the external excitation. Each control system consists of three basic components: (a) a sensing system, (b) a decision making unit, which determines the necessary control actions required to achieve the desired control objectives, and (c) an actuation system that apply control forces determined by the algorithm.

Although the active control methods have been used in electrical, mechanical and aerospace engineering, these methods are not directly usable with civil engineering structures as these structures have their unique set of challenges and different design issues. The reasons for this are:

- (1) Civil structures are massive systems, and therefore the required control force and power can be several orders of magnitude higher than those required for mechanical systems.
- (2) The civil structures also have large degrees of freedom.
- (3) Civil structures and loading on them have larger uncertainties levels. Thus control robustness is an important issue.
- (4) The control system must be extremely reliable, as life safety is one of the primary design criteria for civil structures.
- (5) The functionality control of distributed civil infrastructure system has no

parallel in the mechanical systems, and these will require different innovative control concepts.

- (6) The problem of control of existing structures pose a different set of problems with various constraints, requiring significantly different control solutions

2. STRUCTURAL CONTROL RESEARCH PROGRAM OF NSF

Realizing the potential of the new technology, the National Science Foundation actively sought community opinion through following national and international workshops and panel to start a new research program.

- (1) U.S. Panel on Structural Control Research, established in 1989 under the direction of Professor George Housner.
- (2) International Workshop on Intelligent Structures, Taipei, Taiwan, July 1990.
- (3) Joint NSF-EPRI Workshop on Research Needs in Intelligent Control Systems, Oct. 1990.
- (4) U.S. National Workshop on Structural Control Research, University of Southern California, Los Angeles, Oct. 1990.
- (5) Workshop on Sensors and Signal Processing for Structural Control, Washington, DC, Feb. 1991.

These forums provided the intellectual framework to start a new research initiative entitled Program on Structural Control for Safety, Performance, and Hazard Mitigation by the NSF in 1992 (Ref. 4). The program was initiated for five years. The broad objectives of the program were to foster, on a coordinated basis, multi-disciplinary research and development of passive, active and hybrid control technology for application to buildings and civil infrastructure systems subjected to dynamic

loads. The emphasis of research program was to extend the control concepts so that they can be implemented on civil infrastructure systems, by providing sustained support for the:

- (1) Development of passive, active, semi-active, and hybrid control systems suitable for civil structures.
- (2) Investigations of the robustness and reliability of control systems.
- (3) Development of advance sensors and actuator technology suitable for civil structures
- (4) Development of advance signal processing techniques and their applications in structural control.
- (5) Development of innovative integrated structural and control systems, smart structures, smart materials and sensing devices.
- (6) Sensing and control systems for distributed civil infrastructure systems.

A total of 51 research projects, examining various aspects of structural control have been funded to develop new control methodologies applicable to civil structures. This involves a research expenditure of about \$ 9.6 million over a period of 5 years. NSF has also provided additional support for research in this area through National Center for Earthquake Engineering Research (NCEER) at the State University of New York at Buffalo. The projects have been awarded to academic institutions and private consultant, and are dispersed all over the country. The control concepts that appeared to be futuristic only a few years ago, now seem feasible, primarily due to quantum developments that have occurred in the sensors and information-processing field in the recent past.

The funded projects are focused on research in the following areas:

- Active, passive, and hybrid control technologies for civil structures
- Innovative systems for energy dissipation
- Variable damping and stiffness devices to reduce dynamic response
- New control algorithms applicable to civil structural systems
- Robustness and reliability of control systems
- Actuator dynamics and time delays
- Emerging technologies for structural systems, smart and self healing materials, sensors, remote sensing, monitoring, and diagnostics systems
- Optimal placement of sensors and actuator

The research projects have developed innovative algorithms for application to civil structures. The algorithms that have been used, improved or developed are: feedback control, optimal feedback/ feed-forward control; Lyapunov-based control; bang-bang control; nonlinear optimal control; acceleration feedback control; sliding mode control with linear and nonlinear controllers; fuzzy control; neural-net based control; H_2 and H_∞ controls; adaptive controls; frequency weighted controls; peak response control. The classical control approaches are now being taken to new levels so that they can be applied to massive civil structures.

To apply large forces required by civil structures, several dampers and actuation devices are being considered. Active mass dampers and mass drivers, active tendons, and active bracing systems operated by hydraulic actuators have been used in scaled experiments. The regeneration concept used for stopping and braking of suburban electric trains is being considered to develop the so-called regenerative actuators. The use of potential energy to apply large forces is being considered to develop the so-called gravity actuators. Passive and active liquid

dampers are also being considered for wind response control applications.

Since the reliability of active control schemes is still not established, hybrid control methods utilizing a proper combination of passive and active control approaches are being considered by several investigators to provide desired levels of control over a spectrum of external load effects. Base isolation in combination with active control is one popular hybrid scheme. Controllable sliding isolators, that regulate the friction at the sliding interface, have been examined. This scheme can be effective in achieving a balance between the conflicting requirements of being able to provide only limited sliding displacement one hand and reducing the superstructure accelerations on the other hand. Passive energy dissipating cladding systems in buildings can be supplemented by active devices to enhance the overall system performance. Another concept of mega-substructure control, which utilizes a part of the building mass to act as an active mass damper, has also been explored in analytical studies.

Since the traditional active control of civil structures may require a large power source, semi-active schemes that do not require large power source are being examined. The semi-active devices primarily regulate the structural parameters, such as stiffness and damping, in a timely fashion. In civil engineering community, these schemes have been called semi-active primarily because they do not require a large infusion of outside energy to the structure. In the semi-active systems, structural parameters can be controlled by either of the following dampers: orifice-controlled dampers, friction controllable dampers, electro-rheological dampers, or magneto-rheological dampers. Some of these devices can regulate both the damping and stiffness, and that it can be done without a large power source. The development of

an efficient control algorithm for a semi-active device is, however, more challenging because the problem is highly nonlinear.

The applications of the control systems are being considered for earthquake, wind, wave forces, vehicle loading, and human loading. The structural systems that are being examined are buildings, bridges, distributed systems, and nonstructural subsystems.

To evaluate the performance of different control algorithms, devices, and strategies on a common standardized analytical platform, two benchmark problems have been recently developed. To evaluate the control of earthquake effects, a twenty-story building designed for the FEMA's SAC project has been adopted, whereas for the control of wind induced vibrations, a 76-story building model is used as a benchmark structure. The details of these building are available through Internet on the University of Notre Dame web page at: www.nd.edu/~quake. The investigators are invited to use these models to evaluate their control schemes. There will be 17 technical papers, using these benchmark models, presented at the upcoming 2nd World Conference on Earthquake Engineering to be held in Kyoto, Japan in June 28 – July 1, 1998.

There is also a need to develop benchmark problems for other structures such as bridges. However, since the bridge control procedure are in their very early stage of development, it will be sometime before such a standardized benchmark problem will be available for control scheme evaluations.

One immediate positive outcome of the structural program has been in the area of education. One of the NSF's important missions is to support research that will lead to scientifically educated and well-trained workforce. A direct measure of this

outcome is number of students with masters and Ph.D. dissertation and theses produced in this area of research. Figure 1 shows the

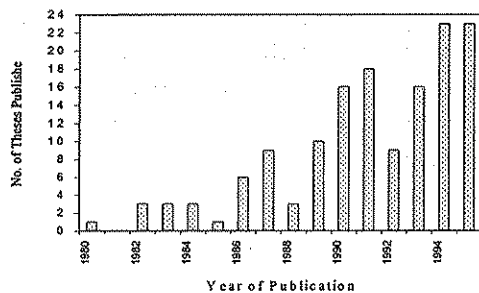


Figure 1: Total Control Theses

total number of theses produced in the area of control. Since the fields of system identification, damage detection, and health monitoring are integral part of the control research, Figure 2 shows the number of

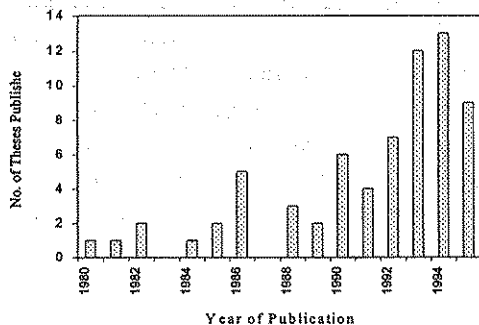


Figure 2: Total System Identification, Health Monitoring, and Damage Detection Theses

theses produced in these particular areas. A clear trend of increasing activity, especially since the beginning of the nineties is quite evident from this data. Since the NSF's research program is primarily focused on the control of civil engineering structures, Figures 3 and 4, respectively, show the number of civil engineering theses produced

in various years in the control area and the system identification, damage detection, and

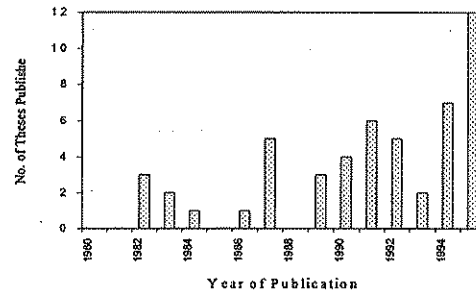


Figure 3: Civil Engineering Control Theses

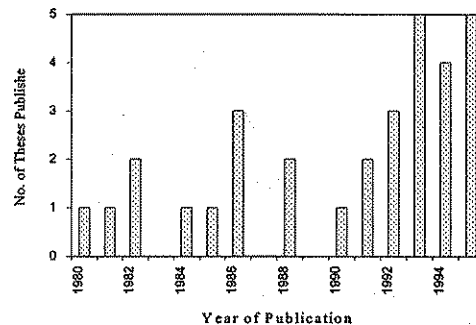


Figure 4: Civil Engineering System Identification, Damage Detection, and Health Monitoring Theses

health monitoring areas. Here again the increasing trend, especially since the beginning of the nineties is quite evident. Figures 5 and 6, respectively, compare the relative level of activity in different engineering disciplines in the two areas. The discipline of civil engineering has clearly taken a lead in research activity in this area. It is quite relevant to mention here that it is this educated workforce that will change the way the civil engineering structures will be designed in the future. This data in Figures 1 through 6 has been

extracted from the report submitted by the US Panel on Structural Control

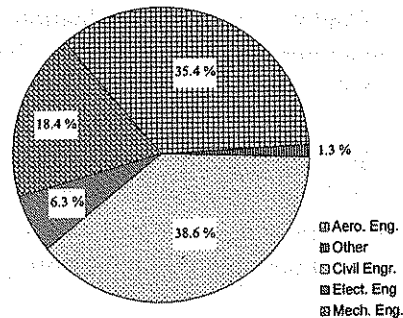


Figure 5: Control Theses Surveyed by Discipline

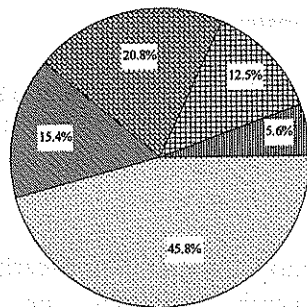


Figure 6: System Identification, Health Monitoring, and Damage Detection Theses Surveyed by Discipline

Research to the National Science Foundation (Ref. 2).

3. PRACTICAL APPLICATIONS STRUCTURAL CONTROL RESEARCH

The final objective of the research program is to utilize the research in full-scale implementations. The passive control schemes are being increasingly used in structural engineering practice. The active, semi-active and hybrid schemes, however, are still in the experimental stage. Japan has taken the lead in using active devices in existing buildings, but only for the low-level wind and earthquake response control. There have been many laboratory experiments on scaled models, attesting to the success of active schemes. These model tests, however, do not address the actual

power and force requirements problem realistically. Similarly semi-active methods with on-off control have been implemented on one or two degrees of freedom simple laboratory models subjected to earthquake type motions. The semi-active devices such as controllable sliding bearings, electro-rheological dampers and magneto-rheological dampers, are getting ready for scaled model demonstration. The experiments have been undertaken to characterize the mechanical characteristics of these dampers. The next step is to develop efficient algorithms and actual demonstration on scaled models. It is expected that full-scale implementation of semi-active devices is likely to occur soon, as the risk involved in their utilization in real buildings are not as much as those with active devices. It is primarily because these devices do not infuse external energy into a structure whereas the active devices do. As for the hybrid schemes, no significant experimental work even on a scaled building model, demonstrating their application in the laboratory, has been reported yet.

Once a concept has been developed, its utilization in practice lies in the industrial domain. That is, the industry must take the bold step of implementing a new technology. In the US, it can be a slow process. Such was the case in the implementation of base isolation and other passive control methods in practice. International collaboration in terms of exchange of ideas and technical data, utilization of complementary resources and strengths of different countries, taking advantage of the differences in construction practices in different countries, can help accelerate implementation of a useful technology. Thus NSF has always encouraged the participation of the US scientists and engineers in international joint research program, exchange programs, international symposium, workshops and conferences. There are many other advantages of international collaboration

such as the (1) elimination of duplication, (2) better identification of research needs, (3) creation and effective utilization of international test beds, (4) improvement of research skills, (5) better educational and exchange opportunities, (6) increased visibility and awareness of earthquake engineering in the general public, and (7) strengthening of research and educational infrastructure for the future.

4. FUTURE RESEARCH NEEDS IN STRUCTURAL CONTROL

Based on a careful assessment of the current research activities in the US and other countries, and the input received from the researchers involved in the structural control program through various workshops and meetings, the following six broad areas have been identified for future research endeavors:

1. Research in passive, active, semi-active and hybrid control with emphasis on nonlinear systems, nonlinear control, nonlinear identification, predictive and adaptive control, actuator saturation, actuator and sensor and malfunction, application to strong seismic inputs, especially vertical components.
2. Research on control of large dispersed and distributed parameter systems (lifelines) with special emphasis on intelligent sensors and fore-warning systems, information processing and decision making systems.
3. Research on high performance, innovative, and intelligent materials
4. Research on system integration with emphasis on hardware/software integration, integrated design of structure-control system, optimal sensor and actuator locations, reliability cost-

benefit considerations, and integration of health monitoring systems.

5. Control system evaluation through analytical and experimental benchmark studies.
6. Education and technology transfer involving training of graduate students, practitioners, and development of design guidelines and code provisions

More details of these broad research areas and the genesis of their development are provided in the reports of the following workshops/meetings.

1. Joint US-Japan Workshop on Mitigation of Urban Disasters: Cooperative Research on Structural Control, Kyoto, Japan, March 14-15, 1996
2. "Fourth Coordination Meeting for NSF Research Program on Structural Control," University of Notre Dame, South Bend, Indiana, October, 4-5, 1996
3. Second International Workshop on Structural Control, Hong Kong, December, 18-21, 1996
4. Fifth Coordination Meeting for NSF Research Program on Structural Control," University of Nevada, Reno, Nevada, August, 18-19, 1997 (Ref. 5)

5. FUTURE PROGRAMS IN HAZARD MITIGATION

The NSF is developing a new Major Research Equipment Program that is intimately related to the area of structural control in hazard mitigation. The program is still in the planning stage. It has also been referred to as the National Network for High Performance Seismic Simulation (NHPS) program. The program is proposed to respond to the need for an integrated

network of experimental research facilities and a new research environment. It is expected to advance the scientific understanding of the impacts of earthquakes. It will help mitigate the effect of disasters attributable to a lack of knowledge about the behavior of engineering materials, soils, and construction during earthquakes. The network will include advanced-design earthquake simulation facilities, large scale testing systems, and field facilities. It will provide a means for the rapid exchange of ideas and information, and offer immediate access to research data generated anywhere in the network. It will also serve as a forum for bringing researchers and practitioners together to share their expertise with students and professionals engaged in earthquake engineering. It will create an environment where students are learning through research that is supported by the latest experimental and communication technologies. It is expected to enhance the synergy and vitality in earthquake engineering.

The objective of NHPS is to advance scientific knowledge, avoid future catastrophes, and protect the populace, built environment and economy in future earthquakes. NHPS will consist of three special purpose (new and enhanced) laboratories to simulate earthquake generated actions on structures and to monitor the motions and response of the built environment during such motions or during actual earthquakes. NHPS will include the following new or enhanced equipment and facilities.

- *Advanced-design earthquake simulation facilities.* To meet the challenge of high-intensity ground motion parameters stipulated by the 1994 Los Angeles and 1995 Kobe events, this NHPS component will include new advanced-design earthquake simulation systems for structural testing and

development of "on-board" shaking units in centrifuges for soil testing. Similarly, the complexities of Tsunami waves and their effects on shorelines and coastal facilities will be studied using an advanced wave generator mounted in a large wave tank.

- *Large-scale testing system.* Failures of structural steel elements in the Los Angeles and Kobe earthquakes have created an exigency for testing structural elements, assemblies of elements, and response modification devices in full scale. These elements exhibit complex nonlinear behavior and require the development of large-scale actuators and improvement of existing capabilities for combined vertical and lateral loading of test specimens.
- *Field simulation and laboratories.* This component of NHPS will comprise field testing installations and mobile laboratory units to monitor the behavior of constructed facilities before, during and after an earthquake. It is needed in order to accumulate behavioral data that cannot be obtained in the laboratory because of difficulties in replicating the structure replete with complications introduced by site, construction, and architectural effects.

This program when implemented will have far reaching effect in the development and implementation of the structural and systems control methods.

6. CONCLUDING REMARKS

The paper describes the development of the NSF's Program on Structural Control. NSF views the research on structural control as an important means for natural hazard reduction. NSF has invested significant resources to initiate this program by funding 51 research projects with a research expenditure of \$9.6 millions. Some of these

projects are still continuing. The researchers are involved in solving several issues related to the control of civil engineering structures. They are developing new algorithms, actuation devices, materials, and new control concepts. Although the five-year program is formally over, the NSF's support of the research activities in this promising area has continued.

The active and semi-active control technologies, however, are not quite ready for implementation in practice. The requirements of large control forces and large external power source are serious impediments in the application of active control. In this respect, the semi-active schemes seem to be more promising for their application to civil structures, as they do not need a large power source. However, these schemes are still in the laboratory-testing phase.

The NSF and the structural control research community consider the coordinated international collaboration and active industrial participation very important component of the program for a successful utilization of this technology.

7. ACKNOWLEDGEMENTS

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