Structural Control, Advanced Sensing Systems and Health Monitoring: Past, Present and Future

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ABSTRACT :

The civil engineering structures are invariably exposed to a variety of natural hazards such as strong winds, earthquakes and water waves which induce dynamic effects. Often not much can be done to reduce the level of such natural hazards to which structures are exposed, and thus for several decades the researchers have focused on reducing the dynamics response by using different types of structural control methods to improve the safety and performance of civil structures. The US National Science Foundation has played a central role for several decades in the development and implementation of innovative methods for passive as well as active structural control. The researchers have developed and improved the concepts of passive and hybrid base isolation, passive energy dissipation methods, and active and semi-active control methods. The in-depth research has identified the strengths and limitations of different control approaches, as well as research issues that need to be further addressed for efficient implementation of various methods. The state of the art of structural control has certainly moved from research to implementation stage with several buildings, bridges and other systems equipped with sophisticated structural control systems. This movement has certainly been facilitated by recent development and continued advancement in sensors and sensing technologies. The structural control schemes are being considered not only for reducing the design level response to enhance life–safety but also to optimally minimize the life cycle costs and maximize performance through performance-based design methods. The active integration of control systems and advanced sensing methods are being examined for overall life time performance improvements through dynamic health monitoring and structural control. This paper provides a historical perspective of the milestone achievements in structural control research and its implementation, and future research trends that are evolving in this field.
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KEYWORDS: Structural Control, Natural Hazards, Earthquake Effects, Sensing systems, Health Monitoring, Performance-based Design, Life-cycle Costs, Resilience, Sustainability.

1. INTRODUCTION

Civil engineering structures, exposed to dynamic effects such as those induced by earthquakes, strong winds and wave loads, are commonly designed for their strength and stability. In the usual design practice, the structural systems are analyzed to calculated forces and deformations in various load-carrying elements such as beams, columns, etc. These elements are then proportioned such that they can withstand the calculated forces and deformations without overstressing or instability failures. The structures are allowed to yield at least for extreme loads such as design level earthquakes to reduce the costs. Such designs, therefore, admit the possibility of structural damage of the load carrying elements in an extreme event. To avoid or limit such damages, structural control approaches have been considered. Both passive and active methods have been developed. The need for controlling the large distributed structural systems led to further advancements in the development of cheap, robust and wireless sensing systems. These developments have also spurred research on the development of effective and reliable structural health monitoring systems for civil structures. Below we provide a historic perspective on the evolution of structural control and how it is now integrated with the most recent advancements in the sensing systems and structural health monitoring.

2. EVOLUTION OF STRUCTURAL CONTROL

In the last four decades, the researchers have examined several approaches to reduce or control the effects of the extreme events with the continuous support form the National Science Foundation, and significant progress has already been made in this direction. These efforts have led to the development of three basic approaches for dynamic response mitigation effects especially for earthquake induced ground motions. The first approach consists of base isolation in which isolators are introduced between the structural foundation and the super structure to primarily filter out the damaging energy of the earthquake motion from reaching the super structure. Basically the isolators are spring supports made of softer material such as rubber bearings which shift the fundamental period of the combined isolator and structure system in to the lower input motion spectrum range. This basic idea has now been implemented in several buildings and bridges around the globe. The continuous research has successfully addressed several important implementation issues and has led to further improvements in the design of isolation devices methods for their practical implementation. The refinements are still being made to improve the performance of these methods using more advanced materials and concepts whereby the characteristic of these systems can be dynamically controlled.

The second approach consists of the use of the energy absorbing devices also called energy dissipaters or energy sinks, placed at suitable locations in structures to dissipate the dynamic energy harmlessly. In the 1980s, a significant level of research effort was devoted to the development of different types of energy dissipation devices as well as in the development of analytical methods that can be used for the design of structures installed with these devices. The devices that were examined were the viscous dampers, visco-elastic dampers, yielding metallic dampers, friction dampers, and their variants. These devices absorb vibration energy that otherwise would have gone to deform and possibly damage the structural elements. Some of them also add stiffness to the structure. With the support from National Science Foundation, the research was done to define the force-deformation-velocity properties of these dampers for their use in structural designs. The analytical methods and approaches were developed to utilize these properties in a simple manner in the design approaches. For optimal utilization of these devices, research was done for optimal sizing, placement of these energy dissipation devices. These devices are robust as they perform well in reducing the dynamic response under varying loading and environmental conditions. The design profession has developed enough confidence in these devices such that they have now been used in retrofit of the older structures as well as new structures to make them carry higher expected loads and more safe for seismic applications. Except for increased initial investment their effectiveness is now well-established. These devises 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 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 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 explored the development of the active control methods for the last twenty years. The NSF again played a central role in these developments by supporting research in this area through well-coordinated structural control research initiatives. This research activity is marked by a series of milestones listed in Table 1.

In the purely active methods, the external forces are applied to control the response. Initially, the application of forces through tendons or other forms of actuators were examined. Significant effort was devoted to develop control algorithms which determine where, when, and how much the forces should be applied to the structure to achieve the desired control objectives. The control algorithms are based on the measurements made on the response of the structure, and sometimes also on the external excitation.

The earlier developments in control engineering in the fields of electrical engineering and aerospace engineering were highly instrumental in motivating the civil engineering community to consider such application to civil engineering structures such as bridges and buildings. These methods used in other discipline were, however, not directly usable with civil engineering structures as these structures have their unique set of challenges and different design issues. The civil structures are massive and distributed systems, and therefore the required control force and power can be several orders of magnitude higher than those required for mechanical systems. The civil structures also have large degrees of freedom. The robustness of the control approach was an important issue with civil structures as they are exposed to loads that have large uncertainties. The control of distributed civil infrastructure system has no parallel in the mechanical or electrical systems. Thus the control of civil structures posed a different set of problems with various constrains, requiring significantly different control solutions.

A 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. One of the most challenging aspect of active control research in civil engineering is the fact that is an integration of a number of diverse disciplines, including computer science, data processing, control theory, material science, sensing technology, as well as stochastic processes, structural dynamics, and wind and earthquake engineering.

Table 1. Structural Control Research – Milestones

Year	Event
1989	US Panel on Structural Control Research (US-NSF)
1989	First actively controlled building constructed in Tokyo
1990	Japan Panel on Structural Response Control (Japan-SCJ)
1991	Five-year Research Initiative on Structural Control (US-NSF)
1993	European Association for Control of Structures
1994	International Association for Structural Control (IASC)
1994	First World Conference on Structural Control (Pasadena, CA, USA)
1998	China Panel for Structural Control
1998	Second World Conference on Structural Control (Kyoto, Japan)
2002	Third World Conference on Structural Control (Como, Italy)
2004	IASC becomes International Association for Structural Control and Monitoring (IASCM)
2006	Fourth World Conference on Structural Control (San Diego, CA,USA)
2008	Fifth World Conference on Structural Control (Columbia University, New York)

To address various research issue involved in the implementation of control methods to civil engineering structures, the NSF formulated a 5-year bold research program on structural control in 1992. This initiative was formulated after a series of activities involving panel formation and discussions at national and international forums and workshops such as: (1) the U.S. Panel on Structural Control Research, established in 1989 under the direction of Professor George Housner; (2) International Workshop on Intelligent Structures, Taipeh, 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 Angles, Oct., 1990; (5) Workshop on Sensors and Signal Processing for Structural Control, Washington, DC, Feb., 1991. 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; and (6) sensing and control systems for distributed civil infrastructure systems.

More than 50 research projects, examining various aspects of structural control were funded under this program to develop new control methodologies applicable to civil structures. This involved 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 the then National Center for Earthquake Engineering Research (NCEER) and now MCEER (Multidisciplinary Center for Earthquake Engineering Research) at the State University of New York at Buffalo as well as other earthquake engineering research centers at the University of California, Berkeley and University of Illinois at Urbana Champaign. The projects were awarded to academic institutions and private consultant. Basic research is still continuing to further advance this concept for its meaningful implementation.

The funded projects focused on research in: active, passive, and hybrid control technologies for civil structures; innovative systems for energy dissipation; variable damping and stiffness devices; 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 developed innovative algorithms such as 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 were considered for application to civil structure with different types of control devices. To apply large forces required by civil structures, several dampers and actuation devices were considered. Active mass dampers and mass drivers, active tendons, and active bracing systems operated by hydraulic actuators were used in scaled experiments. The regeneration concept used for stopping and braking of suburban electric trains was considered to develop the so-called regenerative actuators. The use of potential energy to apply large forces was considered to develop the so-called gravity actuators. Active liquid dampers were considered for wind response control applications.

Since the reliability of active control schemes was still not established, hybrid control methods utilizing a proper combination of passive and active control approaches were also a part of these research efforts to provide desired levels of control over a spectrum of external load effects. Base isolation in combination with active control was one such popular hybrid scheme. Controllable sliding isolators, that regulate the friction at the sliding interface, were examined to achieve 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 were supplemented by active devices to enhance the overall system performance. A few analytical studies also explored the concept of mega-substructure control, which utilizes a part of the building mass to act as an active mass damper.

An observation clearly emerged from these studies that a purely active control scheme in which the control forces are applied from outside is not feasible for application to civil engineering structures primarily because of very large power source requirements. Thus the focus was shifted from active control schemes to the so-called semi-active control schemes. 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, variable stiffness devices, tunable liquid dampers, electro-rheological dampers, and magneto-rheological dampers (Spencer and Nagarajaiah, 2003). Some of these devices can regulate both the damping and stiffness, and that this can be done without a large power source. The development of an efficient control algorithm for a semi-active device has however been a more challenging because the problem is highly nonlinear. These controllable devices have also been called as smart dampers. They offer the reliability of passive devices, yet maintaining the versatility and adaptability of fully active systems, without requiring the associated large power sources. Studies have shown that appropriately implemented smart damping 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 (Dyke et al. 1998). Recently constructed buildings in Japan have employed nearly 800 smart dampers. In civil engineering the major effort was spent on reducing the seismic effects on structures, but the applications of the control systems for wind, wave forces, vehicle loading, and human loading were also considered.

To evaluate the performance of different control algorithms, devices, and strategies on a common standardized analytical platform, bridge and building benchmark problems were developed and well distributed to the research community. The investigators were invited to use these models to evaluate their control schemes. Several technical papers, using these benchmark models, have been presented in different forums such as the World Conferences on Structural Control as well as in technical publications over the last 10 years. This effort is still continuing in an expanded manner to include the structural health monitoring. These coordinated and concerted efforts have accelerated the research-to-implementation process. Control systems have been installed in more than 40 full-scale building structures in four countries, as well as have also been used temporarily in construction of numerous bridge towers or large span structures.

2. STRUCTURAL CONTROL, PERFORMANCE-BASED DESIGNS, LIFE CYCLE COST AND SUSTAINABILITY OPTIMIZATION

The structural control research activities started in the past two decades have also spurred activities in related fields. Earlier structural control was primarily investigated to reduce the dynamic effects. Although the concept was well-understood, its integration in the overall design process was not immediate. When researchers started to feel comfortable with the structural control approaches with all its promises and limitations, the attention was focused on its integration in the structural design process from the beginning. At the same time the concept of performance-based design of civil structures for seismic loads was also taking its roots in the civil engineering communities, primarily motivated by the large economic losses incurred in the 1994 Northridge Earthquake and 1995 Kobe Earthquake. Since both the passive or semi-active structural control methods improve the performance of the structures under dynamic loads, the need for their integration in the performance-based design was quite obvious. Since the performance-based designs try to achieve different performance objectives at different levels of load intensities, the use of the control approaches can help in achieving these objectives better and optimally for a civil structure. The optimality consideration can broadens the scope of the performance-based design to now include the life-cycle cost studies and cost-benefit analyses. The life-cycle cost analyses can be performed for multiple hazard scenarios. In future studies, such analyses must include not only the damage cost but also the economic losses associated with the system recovery costs and resilience. Broadening of integrated structural designs to include other consideration such as the energy costs, carbon imprint, and sustainability issues is also not very far on the future research horizon.

3. SENSOR RESEARCH PROGRAM AT NSF

Due to the rapid advance of sensor, wireless networking and information technologies, and integration of information to the design, manufacturing, operation and maintenance of real-world engineering systems, it is now a time to transform engineering from the past data-poor to the future data-rich world. Recognizing the broad-based interest and great impact potential, NSF's Directorate for Engineering launched a major 3-year research initiative in fiscal year 2003 and invested a total of approximately $125millions over three years on sensors and sensing networks. The initiative emphasized the multidisciplinary research that sought to advance fundamental knowledge in new sensor technologies, including sensors for sensing and detection of toxic chemicals, explosives and biological agents, sensor networking systems in a distributed environment, the integration of sensors into engineered systems, and the interpretation and use of sensor data in engineering and decision-making processes.

Three research thrust areas were identified for solicited proposals in this initiative:

- Design, Materials and Concepts for New Sensors and Sensing Systems
- Arrayed Sensor Networks and Networking
- Interpretation, Decision and Action Based on Sensor Data

As a result of this research initiative and the ongoing research efforts around the world, the sensors and associated technologies have significantly evolved over the last three decades. While the physics behind the transduction process may have not achieved major and revolutionary advances, the overall sensor technology has experienced major strives for enhancements. The research on sensor technology has progressed on three fronts: focus, level of intelligence, and its architecture. These advances are likely to have far reaching impacts on the design of civil infrastructure systems.

4. STRUCTURAL HEALTH MONITORING AND SENSOR SYSTEMS

An essential component of an active structural control scheme is a sensor system to measure the structural states needed in the computations of control algorithms. For the control of civil structures which are usually large and distributed with several dynamic degrees of freedom, it becomes necessary that such a sensing system be accurate, reliable, robust and comprehensive to provide as complete information as possible. For this reason and to measure and collect necessary data about the performance and health of structural systems, as well as the need for accurate sensing in other engineering discipline, the Division of Civil, Mechanical and Manufacturing Innovation (CMMI) in the Directorate of Engineering at NSF now supports a multi-disciplinary research program of research and education in sensor systems and sensor networks with annual expenditure of about $5 millions. As a result of this support, the smart structures technology, an integrated engineering field comprising sensor technology, structural control, smart materials and structural health monitoring is now receiving increased attention from researchers and practitioners. It is expected to bring transformative changes in the design, construction and maintenance of civil engineering structures.

The core of smart structures' technology is the sensor technology as sensors provide the essential data input for processing and utilization by smart structures. For example, the proper functioning of any structural health monitoring system or structural control system relies on accurate sensor data input to the system. Major factors behind the accelerating interest in these areas are the exponential growth in smart materials, electronics, wireless communication, MEMS, structural health monitoring, structural control and information technology, resulting in novel smart sensors with wireless communication, structural control devices, and robust and efficient data analysis and interpretation system. As a result, researchers in academia, government laboratories, and industry are advancing the state-of-the-art of the smart structures technologies with respect to improving the performance, management, and operation of civil structures, as well as effective prioritization of post-disaster rebuilt and recovery actions.

Wireless sensors have been proposed for monitoring the response of large-scale civil structures as they are easy to deploy and possess flexibility in sensor network configuration (Spencer et al. 2004; Lynch and Loh 2006). They are expected to play a more comprehensive role within the smart structure framework. Current research is exploring the inclusion of actuation capabilities within a wireless sensor prototype that allows the wireless sensor to command structural control actuators (Lynch et al. 2006). The wireless sensing network is responsible for the collection of structural response data (e.g. floor accelerations), wireless transmission and communication of response data, calculation of control forces, and application of corresponding force commands to the actuation devices such as an MR damper.

In addition, it is also critical to develop goal focused, self aware sensor intelligence to convert data to useful information that will provide efficacious knowledge; high-performance and low-cost computation; inexpensive wireless communication technology for harsh operation environments; and minimum power-dependence and energy sources capable of scavenging power from the environment. Considering these pioneering technologies and the required characteristics associated with the sensor technology, it is clear that new research and development have to be initiated to realize the anticipated transformation of engineering practices of all fields.

A direct beneficiary of this research activity in sensor systems has been the structural control and structural health monitoring research community. The new generation of sensors is making dramatic impact on environmental and civil engineering problems. Such examples include the structural control and health monitoring of bridges, highways and buildings. In order to sustain performance and reliability of such structures, it is essential to have accurate and real-time information about the condition of the structures. Today information regarding the health of a structure is obtained through scheduled and labor-intensive inspections and analysis, which may not provide the necessary hard information during the critical time before the catastrophic failure strikes. These developments in sensing and senor system have prompted a vigorous research activity in the civil engineering community to develop Structural Health Monitoring (SHM) systems that take advantage of the new generation of sensors.

The basic elements of a SHM system are (a) a sensory system, (b) a data acquisition system, (c) a data processing and archiving system, (d) a communication system, and (e) a damage detection and forewarning decision system. The damage detection involves the identification of the structural damage in terms of location and level of severity, and forewarning systems involved the assessment of the existing condition and remaining service life of the structure. Currently the CMMI Division at NSF funds more than two million dollars on research projects in this area on an annual basis. These research projects are aimed to address the issues of distributed, low cost, dense sensing systems for civil infrastructure systems; development of smart sensing systems with data collection, processing and wireless communication features; and development of methods that can accurate assess the health of the structure and alert about the impending dangers under harsh and uncertain environmental and unusual operating conditions.

5. ROLE OF INTERNATIONAL COOPERATIVE RESEARCH ACTIVITIES

The international collaboration is an important part of the NSF's research activities. The NSF has continuously encouraged and promoted collaborative research activities with international colleagues to leverage intellectual and physical resources synergistically. In the area of structural control, structural health monitoring, and sensor systems, Europe, Japan, China, and Korea have played key roles by participating in several well-coordinated research initiatives.

6. FUTURE RESEARCH ACTIVITIES

The future research challenges in structural control and related discipline are likely to include the control for multiple hazard scenarios, integration of structural health monitoring and structural control, comprehensive life cycle cost-benefit studies considering societal resiliency, carbon imprint and sustainability. At the core of these future research activities will require transformative advancements in sensors and sensing systems. The mimicking of biological systems to enhance the performance of sensors and civil infrastructure systems must be a part of any future research agenda in these areas.

8. CONCLUDING REMARKS

The paper describes the emergence and evolution of structural control as a discipline in civil engineering, and its impact on structural health monitoring and future advances in civil infrastructure component design. The concept of structural control has come a long way in last three decades. It started with the simple objective of reducing the structural response caused by dynamic forces such as earthquake and wind loads to improve the structural safety. Spurred by the research in sensors and sensing systems, this research evolved into the concept of smart structures using smart materials and sensing systems. Its integration in performance-based design in earthquake engineering, structural health monitoring, life cycle-based optimal structural and infrastructure system design, and large system designs considering community resilience and sustainability are strong candidates for future transformative research activities.

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