DEVELOPMENTS IN THE USA IN THE FIELD OF STRUCTRUAL CONTROL AND MONITORING OF CIVIL INFRASTRUCTURE SYSTEMS

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SUMMARY

Since the convening of the Ninth World Conference on Earthquake engineering (9WCEE) held in Tokyo/Luptp om 1988, there has been a growing world-wide interest in the subject of "smart" civil structures that are capable of adapting their characteristics in order to minimize their response under arbitrary dynamic environments. Several national and bilateral workshop have been convened in the recent past to deal with various aspects of intelligent structures and materials, and the International Association for Structural Control (IASC) was officially formed in 1994 to operate along the same organizational structure of IAEE. A brief historical review is presented.

This paper gives an overview of recent research and development activities in the USA in the various aspects of the general field of structural control and monitoring of civil infrastructure systems. Both national and international collaborative activities are discussed, and future joint research initiatives in the field are presented.

INTRODUCTION

The general field of Structural Control deals with the monitoring and control of the motion of civil infrastructures under the action of natural or man-made dynamic environments. Many different types of control are now studied and utilized and, in fact, from the control point of view almost all activities of man can be viewed as examples of control, either technical or social. In the fields of engineering, control plays an important role, for example, in electrical engineering, in applied mechanics, in space structures, in mechanical engineering, etc. In these fields much research has been done on control theory so it might appear that all the problems of structural control have been solved, but this is not so.

The nature of control theory and practice is largely determined by the particular application under consideration, and the subject of structural control has distinctive features that govern the direction of research. For example, it focuses on the performance of relatively massive structures; it involves excitations whose precise properties are not known beforehand; it may require dissipation of large amounts of kinetic energy; it involves the application of relatively large counter-forces but is concerned with only relatively low accuracy of control; and it has the potential for important benefits to the public safety and economy.

The excitations of concern are earthquake, wind, and man made forces. There are different approaches to controlling, but not necessarily eliminating, unwanted motions of structures: passive methods such as base-isolation or tuned-mass dampers; active methods in which counter-forces are applied to reduce the motions; combined active and passive methods of control; methods of varying structural stiffness; controlled damping; etc. The objective is to utilize the most effective combination of these methods to control structural vibrations.

The ultimate goal of research on structural control is practical application to real structures, with an acceptable cost. When considering practical applications, any related subjects must also be examined, for example: motions and strains must be monitored; sensors must be developed of various types; relevant material properties must be

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studied; damage detection and health monitoring methods must be developed; problems in "system identification" will be encountered, etc. Two different goals of structural control must be given consideration: the utilization of control in the design of new structures, and the utilization of control to improve the seismic resistance of existing structures. The problems posed by existing structures differ from the problems of designing new structures because of various constraints imposed. In California, the Government requires that hospitals be functional after an earthquake, and new hospitals and existing hospitals incorporate some form of structural control.

In many cities the infrastructure is inadequate, obsolete, inefficient, and potentially hazardous during earthquakes; and this requires special study and planning for future improvements. The subject of structural control offers opportunities to design new structures and to retrofit existing structures by the application of counter-forces, smart materials, frictional devices, etc., instead of just increasing the strength of the structure at greater cost. A variety of applications already have been installed in building structures to control wind induced motions that are objectionable to the occupants; and many applications of passive control, such as base isolation, have been installed to reduce structural accelerations produced by strong earthquake ground shaking. There is a consensus that structural control has the potential for improving the performance of structures, new or existing, if appropriate research and experimentation are undertaken.

INITIAL PHASE OF STRUCTURAL CONTROL

In 1989, the US Panel on Structural Control Research was established with the support of the US National Science Foundation to assist in coordinating the national activities in the field of Structural Control and to facilitate the cooperation between US and international collaborators in the field. In 1991, under the leadership of Dr S C Liu of the Hazard Mitigation Program, NSF initiated its five-year research program on structural control for safety, performance and hazard mitigation.

Since 1991, there has been an increase of interest in this field by U.S. researchers, and also more applications to actual structures. As a result, there has been a significant increase in the number of US researchers engaged in work on structural control and this in turn is leading to more diverse related research activities. Recent US activities in active and hybrid structural control can be grouped into the following areas: (a) Control algorithm and modeling, (b) Sensing and actuation, (c) Hybrid control, (d) Implementation issues, and (e) International cooperation.

In 1994 the International Association of Structural Control (IASC) was officially established. The First World Conference on Structural Control (1WCSC) was held in 1994 in Pasadena, California with 250 attendees. The Second World Conference on Structural Control (2WCSC) was held in 1998 in Kyoto, Japan. Numerous research publications have appeared in national and international journals. The Journal of Earthquake Engineering and Structural Dynamics is now the official journal of the International Association for Structural Control and is publishing control papers. The Loma Prieta earthquake and Northridge earthquake have created much interest in control among practicing engineers and a number of newly designed hospitals employ a type of combined base isolation and dampers to assure functionality following an earthquake; and control techniques are being employed on retrofitting important public buildings and even some high tech factory facilities. A milestone was achieved by having in 1996 the very first application of active control techniques to an actual civil infrastructure system in the U.S. - the equipping of an important interstate bridge in Oklahoma by an active structural control device to reduce dynamic stresses. Three U.S./Japan Workshops on structural control have been held in the U.S., Japan and Hong Kong, and the U.S. Panel has participated in organizing two workshops in Europe and one in China. The Bibliography provides a listing of the published proceedings of the cited workshops and conferences on Structural Control.

U.S. Ph.D. Activities in Structural Control

A survey of graduate student theses published in the United Sates since 1980 shows a steady and significant increase in research in structural control and related technologies, such as system identification, health monitoring, and damage detection. Although this trend is not unexpected, it is interesting to note that more than 75% of theses devoted to these topics over the past 16 years have been written since 1990. Because much of the structural control research relevant to civil engineering applications is based on technologies which overlap with similar research in other engineering disciplines, the theses represented in the final compiled data originated from several engineering disciplines, including electrical, aeronautical, mechanical, as well as civil engineering (IASC Newsletter, 1997).

This significant increase in research in the various technical components of the structural control field can be attributed to several factors: (1) increased interest and acceptance of "smart" technologies by the overall engineering community as a viable means of damage mitigation; (2) the NSF-sponsored initiative on structural control research; and (3) the increased profile of these research areas, as illustrated through the organization of conferences and workshops, the new technical committee on control through the American Society for Civil Engineers (ASCE), the formation of the International Association of Structural Control, and various publications.

U.S. RESEARCH ACTIVITIES IN STRUCTURAL CONTROL

Since the U.S. National Science Foundation (NSF) initiated its five-year research program on structural control for safety, performance and hazard mitigation in 1992, (NSF, 1991), there has been a surge of interest in this field on the part of U.S. researchers. As a result, there has been a significant increase in the number of U.S. researchers engaged in this field, leading to more diverse research activities. A complete listing of the titles of all NSF funded research grants under this Initiative is provided in the Appendix.

Recent U.S. activities in active and hybrid structural control can be grouped into the following areas:

Control algorithm and modeling

Sensing and actuation

(c) Hybrid control

(d) Implementation issues

(e) International cooperation

A tutorial paper titled "Structural Control: Past, Present and Future" (Housner, et al., 1997) was recently published. This tutorial/survey paper (1) provides a concise point of departure for researchers and practitioners alike wishing to assess the current state of the art in the control and monitoring of civil engineering structures, and (2) it provides a link between structural control and other fields of control theory, pointing out both differences and similarities, and points out where future research and application efforts are likely to prove fruitful. The paper consists of the following sections: Section 1 is an introduction; Section 2 deals with passive energy dissipation; Section 3 deals with active control; Section 4 deals with hybrid and semi-active control systems; Section 5 discusses sensors for structural control; Section 6 deals with smart material systems; Section 7 deals with health monitoring and damage detection; and Section 8 deals with research needs. An extensive list of references is provided in the Bibliography section.

A monograph focusing on the accomplishments of the research projects sponsored by NSF is under preparation (Soong and Singh, 1997). This document is intended to serve as an up-to-date resource material for the work done on structural control. Each principal investigator (PI), awarded a research grant by NSF, is expected to contribute to the monograph. The contributions are in the form of either individual papers giving the findings of the research projects by each PI, or collaborative papers written with other principal investigators where there is some overlapping work or research interest. Each paper will describe the main thrust of the research giving formulations, algorithms, new hardware and software developments, and significant results. Each project PI is allotted 25 single-spaced pages for his/her contribution.

RECENT INTERNATIONAL ACTIVITIES IN STRUCTURAL CONTROL

Since the convening of the Ninth World Conference on Earthquake Engineering (9WCEE) held in Tokyo/Kyoto in 1988, there has been a growing world-wide interest in the subject of "smart" civil structures that are capable of adapting their characteristics in order to minimize their response under arbitrary dynamic environments. Several national and bilateral workshops and conferences have been convened in the recent past to deal with various aspects of intelligent structures and materials. A listing, as well as a copy of the Proceedings of such workshops and conferences that were specifically concerned with civil structure are available from the web page of the U.S. Panel on Structural Control Research at http://cwis.usc.edu/dept/civil_eng/structural/welcome.html

In addition, several countries have established, or are in the process of establishing, formal organizations to coordinate their respective national activities in the field of structural control. These activities are a clear indication of the breadth of interest in this promising and challenging field.

FUTURE RESEARCH NEEDS

Research Topics

The earthquakes of 17 January 1994 in Northridge and of 17 January 1995 in Kobe, being moderately large earthquakes occurring in modern urban regions, provided earthquake engineers with valuable information about the performance of civil infrastructure systems subjected to near-source ground motion. While the performance of most systems during these earthquakes was quite predictable and duplicated previous experience, there was some unanticipated structural behavior as well as some encouraging structural performance of systems incorporating modern protective systems. Some of the significant engineering features of the earthquakes have important implications for the broad field of Structural Control. Specifically, these earthquakes emphasized the need for focusing on issues dealing with the modeling, monitoring and control of structural systems in urban regions subjected to strong earthquake ground motions.

On the basis of the technical discussion presented in the preceding sections, and in view of the performance of civil systems with structural control devices during the recent earthquakes, it is recommended that the following topics be given high priority for research investigations:

* Devices and algorithms for passive, active, semi-active and hybrid control of nonlinear systems, with emphasis on energy-efficient approaches and hardware for handling strong inputs.

* Modeling and identification of nonlinear dispersed civil infrastructure systems.

* Development of innovative, high performance, and intelligent material systems.

* Health monitoring, condition assessment and damage detection of dispersed civil infrastructure systems.

* Intelligent sensors for distributed sensing and control in dispersed systems.

* Near-field strong earthquake ground motion issues impacting structural control applications.

* Collaborative national and international studies of system evaluation and performance comparison based on large scale structural tests.

Structural Control Task Groups

The American Society of Civil Engineers (ASCE) in coordination with the U.S. Panel on Structural Control Research, has established three Task Groups on Structural Control:

1. Task Group on Benchmark Control Studies

2. Task Group on Health Monitoring

3. Task Group on Codes for Structural Control

This will implement the recommendations, concerning the mission and scope of work of the planned Task Groups, based on the deliberations of participants in the Second International Workshop on Structural Control (Hong Kong, 1996). The planned Task Groups will work in close cooperation with the US Panel, as a member of the International Association for Structural Control, and thus be in contact with corresponding Task Groups in other countries. The activities of the Task Groups will be coordinated by IASC.

The main goals of the Task Groups, are:

- **Task Group on Benchmark Control Studies**: to initiate the development of a series of representative benchmark problems that can help to focus structural control research for buildings. However, since it is impractical, both financially and logistically, for all researchers in structural control to conduct experimental tests, development of high-fidelity analytical benchmark problems is an important

- **Task Group on Health Monitoring**: to prepare plans for a series of international benchmark studies of proposed methodologies for structural health monitoring using response data from full-scale structures in damaged and undamaged states. For the purpose of working towards this goal, the structural health monitoring system is defined as any non-destructive evaluation technology for damage detection, location and/or assessment using structural response data.

- **Task Group on Codes for Structural Control**: to (1) survey and summarize existing codes and guidelines for base isolation and passive damping control systems, (2) develop a general philosophical basis for the use and design of structural control systems, and (3) recommend a draft outline of guidelines for the design of structural control systems.

CONCLUSION

Based on the preceding discussion, it seems highly desirable to encourag structural engineers and architects to seriously consider exploiting the capabilities of structural control for retrofitting threatened existing structures and also enhancing the performance of prospective new structures that may be subjected to strong earthquake shaking.

Even though a considerable amount of progress has been achieved in the field of structural response control using various passive and active approaches, there are still many diverse research topics related to the control and monitoring of structural systems that need study and await resolution before the promise of the smart structures and materials technology is fully realized in the context of seismic response control of civil infrastructure systems. Progress in this field will be speeded by multi-national efforts involving world-wide collaborative research projects, exchange of personnel, jointly organized tests, and exchange of data and technical information.

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The Earthquake Hazard Mitigation Program of the U.S. National Science Foundation has had a major influence on the initiation and growth of the broad field of structural control of civil infrastructure systems. Particular credit is due S.C. Liu for encouraging the activities of the U.S. Panel on Structural Control Research, which is administered by the California Universities for Research in Earthquake Engineering (CUREe). The recent five-year Structural Control Initiative of NSF under the leadership of S.C. Liu, K. Chong and E. Sabadell has provided funds to launch many research projects.

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APPENDIX

Projects Awarded in FY92:

1. Active Control of Structures using Neural Networks
2. Structural Control of Earthquake and Wind Storms using Active Structural Members,
3. Safety and Performance Enhancement of Structures Through Structural Control,
4. Exploring the Problems in Active Structural control & Health Monitoring of Existing Constructed Facilities by Utilizing a Decommissioned Steel Truss Highway Bridge,
5. Control of Occupant-Induced Floor Motion,
6. Development of Adaptive Hybrid Control Techniques for Building Structures,
7. Hybrid Control of Building Seismic Response using Architectural Cladding,
8. Active Tuned Liquid Damper for Structural Control,
9. Passive Smart Cementitious Composites for Dynamic Control Structures: Internal Timed Release of Chemicals for Self-Repair of Crack Damage
10. Active Control of Structures using Neural Networks
11. Structural Control for Phase-Related Inputs,
12. Studies of Integration and Implementation Issues in the Active Control of Lifeline Systems

Projects Awarded in FY93:

1. US/Korea Joint Research on Hybrid System for Seismic Structures with Resonant Dampers and Robust Multiobjective Controllers
2. A Hybrid Sliding Isolation System with Controllable Friction Bearing
3. Active Control Using an Aeroelastic Model of a Dome
4. Robust Nonlinear Decentralized Control of Cable Supported Bridge Structures
5. Robust and Reliable Control Algorithms for Practical Implementation on Full-Scale Structures
6. Passive and Active Control of Structural Response
7. Mass Dampers for Vibration Control
8. Electrorheological-Fluid Dampers: Testing Modeling and Application in Vibration and SeismicProtection of Buildings and Bridges
9. Control System for Highway Load Effects
10. Sliding Mode Control of Structures with Regenerative Electric Actuators
11. Development and Performance Evaluation of Low Power Intelligent Structural Control Systems
12. Development and Performance Evaluation of Low Power Intelligent Structural Control Systems
13. Reliability and Safety of Structures using Stability-based Hybrid Controls
14. Reliability Study on Hybrid Controls of Flexible Uncertain Structures under wind Loads Structural Control Research: Tuned Liquid Dampers

Projects Awarded in FY94:

1. Implementing Active Control Under the Ballroom Floor of the Cincinnati Convention Center
2. Optimal Hybrid Control of Buildings with Nonlinear Hysteretic Cladding Connection Elements
3. An Active Damper System for Hybrid Control of Bridges under Earthquakes
4. First World Conference on Structural Control
5. Torsional - Bending Vibrations Attenuation using Piezoelectric Elements
6. Design of Controllable Civil Engineering Structures
7. US/PRC Joint Research Program on Structural Control

Projects Awarded in FY 95:

1. Robust Structural Control for Hazards Mitigation using Probable and Possible Models
2. Active Control of Structures using Neural Networks and Fuzzy Logic
3. Active Control of Floor Vibration, University of Miami
4. The Next Generation of Tuned Liquid Dampers for Controlling Structural Motion