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Current Directions of Structural Health Monitoring and Control in USA

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ABSTRACT Structural Health Monitoring (SHM) is an important and growing field in civil engineering. The goal of SHM techniques is to identify, quantify and locate damage in structures. In light of the aging infrastructure and recent failures of important bridges, long-term monitoring techniques are being increasing investigated and adopted. In addition to SHM, structural control (SC) is increasingly adopted in modern structures around the world. In the past two decades a number of SC techniques, including, passive, semi-active, and active control methods have been developed and adopted in civil engineering–particularly, in infrastructure such as important tall buildings, critical facilities, and long span bridges. Both SHM and SC technology face significant challenges due to the size and scale of civil engineering structures. In response of these challenges researchers in the U.S.A and around the world have developed new and innovative techniques.This paper summarizes some of the ongoing research in the U.S.A. in the area of monitoring, damage detection and control in civil engineering structures.

INTRODUCTION

Enhancing the performance of structures against natural and man made hazards is the motivation for civil engineers to develop new monitoring and control technologies. In addition, monitoring the health of existing infrastructure, damage detection and damage isolation is also critical for life-safety. Aging elements in massive civil engineering infrastructure–if not monitored and repaired in a timely fashion–can cause sudden and catastrophic failures such as I-35W Mississippi river bridge collapse in August 2007. In light of such recent failures of important bridges around the world long-term structural health monitoring (SHM) techniques are being increasing investigated and adopted. In addition to SHM, structural control (SC) is increasingly adopted in modern structures around the world. Recent research has increasingly focused on development of smart structures that involve SHM and SC technology, smart wireless sensors, appropriate algorithms and implementation aspects.

Since the boundaries of traditional designs and modern structures are continuously stretched the structures become more and more complex. For such structures visual inspection is increasingly challenging, time-consuming, expensive, and in certain cases flawed. There are also questions of the consistency of the conclusions of these inspections. In a recent report by the Non-Destructive Evaluation Validation Center in McLean, Virginia [1], inspection reports differed considerably due to lighting conditions, fear of traffic, and experience of the inspector. Additionally, it is difficult to access certain structural elements due to limitations in the inspection equipment.

Future buildings and bridges will have built-in monitoring systems that can tell the owner that repair or maintenance is required, how immediate the need for maintenance is, where in the structure is the damage located, and how long the structure is expected to be useful based on anticipated usage patterns. These systems will enhance performance and reliability of the structures, while decreasing life-cycle costs, including maintenance and inspection costs.

Passive strategies are relatively well-understood and widely accepted by the engineering community as a means for mitigating the damages from unfavorable dynamic loads. However, passive systems cannot adapt to the structural changes and the changing environment. Active, hybrid and semiactive control systems are a natural evolution of passive technologies. The devices integrate with real-time controllers and sensors within the structure. They act simultaneously with the hazardous excitation and structural responses to provide enhanced behavior for improved service and safety. Use of structural control devices is expected to facilitate significant advancements toward performance based design of structures. A great deal of research has been performed in the last two decades in structural condition monitoring and structural control. The main focus of this paper is to describe the latest developments in the field in the United States.

STRUCTURAL HEALTH MONITORING

Smart Sensor Networks 'Smart' sensors with embedded microprocessors and wireless communication links have the potential to change fundamentally the way civil infrastructure systems are monitored. The recent development of the smart sensors, wireless communication, and information technologies has made SHM with a dense array of sensors possible [2][3]. Nagayama et al. have described the issues in structural health monitoring employing smart sensors [4].

The Berkeley Mote smart sensor [3] has emerged as an important open hardware/software platform for SHM [5]. However, the available sensors are limited and are not necessarily optimized for civil infrastructure application. Recently, Intel developed the Intel-Mote that fully supports TinyOS. Efforts at Intel provide an important indicator of the bright future of this technology. Smart sensors based on the Berkeley Mote and Intel Mote platforms will provide the impetus for the development of the next generation of SHM systems. Nagayama et al. [6] have recently perfomed structural health monitoring utilizing Intel's Imote2 wireless sensor platform.

SHM algorithms which can take advantage of the distributed computing environment offered by smart sensor technologies are currently limited. Development of the SHM methods that mesh well with the smart sensor technology is highly desired. Researchers at University of Illinois at Urbana Champaign [7][8] have proposed and tested a distributed computing strategy (DCS) which is suitable for implementation of SHM using a dense array of smart sensors. In the proposed DCS, adjacent smart sensors are grouped together, with only local measured information being employed to evaluate the condition of local elements and using the flexibility based damage detection technique using damage locating load vectors developed at Northeastern University [9] [10].

At Washington University in St. Louis researchers have also experimentally validated a decentralized approach based on the Damage Location Assurance Criterion (DLAC) method using wireless sensor networks based on iMote2s [11]. With this technique one can detect and locate structural damage by evaluating the linear correlation between frequency change vectors obtained by experimental measurements and an analytical model. The method is completely decentralized; all computations can be made at the sensor level. Experimental validation has been performed on two test structures, a steel beam and a 10-bay truss used by Nagayama, et al [4].

Smart Sensors Wireless structural monitoring systems have been shown to provide equivalent data acquisition performance compared to traditional tethered monitoring systems at substantially reduced costs [12]. The fundamental building block of a wireless structural monitoring system is the low-cost wireless sensing unit. Wireless telemetry (wireless radios) and mobile computing (embedded microcontrollers) are combined with sensors to both reduce the cost of installing the system (by eliminating expensive cabling) and allow the sensor to take responsibility of their own measurement data. Recently, the wireless structural monitoring paradigm has been extended to include opportunities to actuate and control the structure being monitored. Lynch [13] proposes a wireless active sensing unit that includes in its architectural design an actuation interface to which active sensors and control actuators can be attached and commanded in real-time. This allows active sensors, such as piezoelectric elements, to simultaneously excite structural components, to which they are attached or embedded, within while recording the corresponding structural response.

Multifunctional Materials as Sensors The idea of using the peizoresistivity (change in resistance with strain) of single walled Carbon nanotube (SWCNT) based films produces a new approach to strain sensing [14] [15] [16]. Their piezoresistive behavior is a linear function of the induced strain. Experimental results [14] [15] [16] have proved that there exists a linear relation between the change in resistance and the strain. Studies on the correlation between mechanical deformations and electronic properties of single-walled CNTs (SWCNTs) have shown that such materials can be used effectively for strain sensing. Carbon nanotubes also offer an attractive alternative as they can be embedded into composites so that they enhance strength and provide sensing capability thus leading to a multifunctional material [14] [15] [16]. Wireless sensors can also be used as a low-cost method of introducing electrical signals into cementitious structural elements. Lynch et al.[16] have observed that the cementitious materials (e.g. fiber reinforced cementitious composites (FRCC)) are semi-conducting materials and they exhibit piezoresistive properties when mechanically loaded. Flexible piezoelectric paint developed at University of Maryland based low-profile surface mounted or embeddable acoustic emission (AE) sensor can be used for bridge load carrying capacity evaluation [17]. This paint has flat frequency response over ultrasonic frequency band from 40 kHz to 1 MHz that makes wide-band ultrasonic sensing and waveform based AE signal interpretation possible. Researchers at Missouri Institute of Technology have developed a distributed cable sensor [18].

ALGORTIHMS

Signal Processing and Adaptive System Identification Techniques Research efforts conducted at the University of California, Irvine include developments of new on-line adaptive techniques for tracking the variation of structural parameters due to damages [19][20][21]. For the on-line identification of the variation of structural parameters due to damages, new adaptive tracking techniques have been developed by Yang and Lin based on the least square estimation (LSE) and extended Kalman filter (EKF) [19][20][21]. Data compression techniques have been investiagted by Zhang et al. [22].

Nonlinear and Hysteretic Models Pei and Smyth [23][24] have worked on the modeling problem of nonlinear and hysteretic dynamic behaviors through a constructive approach which exploits existing mathematical concepts in artificial neural network modeling. In contrast with many neural network applications, which often result in large and complex 'black-box' models, here, they strive to produce phenomenologically accurate model behavior starting with network architectures of manageable/small sizes. This affords the potential of creating relationships between model parameter values and observed phenomenological behaviors, the feature of which is desirable in applying data-driven techniques such as neural networks in damage detection. To demonstrate that conventional and soft computing approaches can be unified in the context of creating a neural network approach with enough physical/mathematical/ phenomenological insights to be classified as meaningful, but yet remain highly adaptive, Pei and Smyth applied this neural network approach to represent nonlinear dynamic response using the restoring force-state mapping formulation. It has been shown that by streamlining the networks, individual network model parameters take on physically or geometrically interpretable meaning. In other work in nonlinear system modeling based on vibration response data, Smyth and others previously have noted the challenges associated with using displacement or velocity measurements obtained from integrated accelerograms. Following ideas by Crawley and O'Donnell, Smyth demonstrated how using, for example, coarse GPS obtained displacement measurements one might enhance collocated high-precision accelerometer information to yield enhanced estimates of all of the measurement states [25]. Full-scale application of the technique was demonstrated on a large suspension bridge [26]. More recently Chatzi and Smyth [27] extended the idea of data fusion together with system identification using non-collocated heterogeneous sensors on MDOF systems which exhibited hysteretic behavior.

Structural Damage, Actuator, and Sensor Fault Detection Alogrithms Recent research at Rice University has led to the development new techniques such as interaction matrix formulation and input error formulation, based on the concept of analytical redundancy, to detect and isolate the damage/fault in structural members, sensors, and actuators in a structural system [28][29][30] [31]. The techniques can detect the presence of fault/damage in a structure (level 1), locate the member/sensor/actuator in which fault/damage is existent (level 2), and determine the time instants of occurrence (level 3). The resulting error function would indicate real time failure/damage of a member, sensor or actuator. The interaction matrix technique allows the development of input-output equations that are only influenced by one target input. These input-output equations serve as an effective tool to monitor the integrity of each member, sensor or actuator regardless of the status of the others. The procedure requires the knowledge of analytical model of the healthy system being tested, the analytical redundancy can be experimentally predetermined through input-output based system identification. Additionally, Rice researchers [31] have developed a ARMarkov observer bank algorithm to detect the extent of damage (level 4). Research at Rice University has shown, experimentally, that the proposed algorithms successfully identify failures of actuators or sensors [28] [29] [30] that are attached to the truss structure in tests on the NASA 8-bay 4 meter long truss. Considering the limited number of measurements and the complexity of the structure, test results ensure the capability of proposed procedure in detecting and isolating the simultaneously and arbitrarily occurred multiple failures.

Fault Detection and Control Fault tolerance is defined as the ability of a control system, in the presence of a fault, to maintain control objectives although performance may suffer somewhat. Although a control system should be designed to employ devices and hardware with the greatest reliability, it is best to be prepared in the unlikely event of a fault in the system. In general, a fault tolerant system has two components: i) fault detection and identification, and ii) fault accommodation. Narasimhan et al. [32] have developed neural network based fault tolerant controllers.

Finite Element Model Updating Song et al [33][34] have developed a new approach for model updating in complex structures that is suitable for SHM. A subset selection method is used in conjunction with damage functions, thereby efficiently reducing the size of the original updating problem. The System Equivalent Reduction Expansion Process (SEREP) is applied to enhance the information available from the sensor data. The method was successfully applied numerically to a concrete shear wall as well as several trusses. This method has also been extended for use in updating nonlinear models of damaged structures [35].

Many model updating methodologies optimize objective functions comparing the characteristics of the model being updated with the corresponding characteristics of the real structure extracted from experimental data. Due to the limited number of sensors, and the high number of parameters to be updated the objective function could have more than one local minimum. One can argue that due to noise in the sensors and modeling errors a local minimum could be a better representation of the real physical characteristics of the structure than the global minima.

Researchers at the University of South Carolina have focused in identifying the local minima of the objective function and their respective probabilities, giving the analyst a series of plausible models. The analyst selects one or multiple models for subsequent analysis based on his/her experience and additional observations not captured in the experimental data or objective function [11][36][37].

Work at the University of South Carolina has focused in the identification of mode shapes with high spatial density [38][39]. Their proposed methodology consists in a moving sensor that captures acceleration data as it moves, resulting in a record of acceleration as a function of time and location. High density measurements of the mode shapes can be calculated from this single acceleration signal.

Song and Dyke [36] developed an approach to the sensor placement problem that allows the designer to obtain the placement with the smallest uncertainty in the results of an ARMAv identification process. The approach uses a information entropy (differential entropy) measure, as well as various matrix norms, to measure the uncertainties embedded in the ARMAv model estimates.

Nondestructive testing and evaluation techniques Techniques that provide unambiguous results are essential for cost effective and timely evaluation of civil infrastructure systems. Subsurface sensing technologies that seek to identify and locate invisible anomalies beneath the surface include ground penetrating radar, infrared thermal imaging, ultrasonic pulse, electromagnetic induction, hyperspectral, and impact echo. Model based assessment strategies for diagnostics and damage detection algorithms [9][10] are under development through NSF IGERT Intelligent diagnostics at Northeastern University headed by Sarah Wadia-Fascetti. Ultimately, a physics-based link between the environmental conditions that cause the damage, the damage itself, and the sensors that measure the effects of the damage is required for a holistic diagnostics approach. Integration between model based assessment at the local level and finite element updating can provide that link.

SHM using NExT and ERA

At Washington University the research has focused on developing a model-based technique to identify structural parameters in both pre and post damage scenarios and the implementation of techniques that accommodate the influence of environmental conditions on modal parameters. The identification of structural damage consists of first determining the modal properties of the structure, and then obtaining a least squares solution to determine the stiffnesses associated with an identification model representative of the system behavior. When ambient vibration is available, a combination of the Natural Excitation Technique (NExT) with the Eigensystem Realization Algorithm (ERA) is carried out to determine the dynamic features. Verification of this technique has been performed with analytical and experimental model of the Bill Emerson Memorial [33].

To date, few studies have considered how to accommodate changes in environmental conditions such as temperature, temperature gradients, and humidity, which may affect dramatically the accuracy of the methodologies. Principal Component Analysis (PCA) is a multi-variate statistical method that can help to reduce the effect of these factors when identifying structural parameters for damage detection. This statistically-based analysis has been used to accomodate the effects of environmental factors that affect the behavior of the structure [40]. In addition, the effect of noise in sensors can also be mitigated when a large number of samples is employed.

Application of Sensors and Algorithms to Real Structures A handful of full scale structures have been used as test-beds in the U.S. for the development or validation of condition monitoring strategies. For instance, the Millikan library on the campus at California Institute of Technology has been instrumented and since, then California Strong Motion Instrumentation Program has installed sensors in numerous buildings in California. The Alamoso and I-40 bridges in the southwest and the Bill Emerson Memorial bridge in the midwest have been instrumented and studied. Several other bridges have been instrumented, temporarily or permanently, for characterization and damage detection purposes. The most recent being the Golden Gate bridge instrumented with a wireless sensor network by Fenves et al. [41]. Some specific examples are discussed below.

The research and development activities of Bridge Research Center at the University of Illinois at Chicago include projects on advanced sensor and sensor network technology, NDE technology, and health monitoring for bridge and large civil structures. Recent research on sensor technology and sensor network technology concentrate on EM sensing technology , PVDF transducer, and wireless smart sensor network [42][43]. Magnetoelastic sensing technology [44] is a promised nondestructive testing technology for monitoring stress and corrosion in steel. Currently it is the only method to directly measure stress in steel cables. The EM sensors developed have been used to measure and monitor the force of pre-stress tendons and cables on bridges and dome in US, China and Japan. Recently, the EM sensors have been used to monitor the hangers and pre-stress tendons in QianJiang 4th Bridge.

As to structural health monitoring and its evaluation technology, a distributed bridge health monitoring system has been investigated for monitoring bridge structures for excessive strains, deflections, load distributions, and temperature variations and installed on Kishwaukee Bridge, Illinois [44]. Such monitoring would not only warn if any excursions deviate from accepted values, but also evaluate the working condition of the bridge monitored in realtime. It implements modular design and uses distributed data collecting and processing strategy.

Structural health monitoring applications to real structures have been conducted at the University of Southern California (USC) by a team of researchers that have developed and applied a web-enabled structural health monitoring system that is optimized for the continuous real-time monitoring of dispersed civil infrastructures such bridges [45]. An updated version of this web-enabled SHM system was used to capture the recent collision of a ship with the Vincent Thomas Bridge in the metropolitan Los Angeles area [46]. The USC team has also used SHM approaches to track the structural changes in a full-scale building being retrofitted [47]. Additionally, the USC team has applied a novel approach for the structural identification and monitoring of a full-scale 17-story building based on ambient vibration measurements [48].

STRUCTURAL CONTROL

Researchers have investigated the possibility of using active, hybrid, and semi-active control methods to improve upon passive approaches to reduce structural responses [49]. The Kajima Corporation accomplished the first full-scale Active Mass Damper application of active control in the 11 story Kyobashi Center building in Tokyo, Japan [50]. Although extensive analytical and experimental structural control research has been conducted in both the U.S. and Japan in the last decade none of these full-scale active control installations are located in the USA–with the exception of one experimental system installed on a bridge in Oklahoma [51]. Recent research in U.S.A. has focused on semi-active control strategies that offer the reliability of passive devices [52], yet maintaining the versatility and adaptability of fully active systems, without requiring the associated large power sources and can operate on the battery power. Studies have shown that appropriately implemented semi-active 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 reductions during a wide array of dynamic loading conditions [49].

Semiactive Devices The most important semi-active damping devices have been developed by the use of variable-orifice controllable valves to alter the resistance to flow of a conventional fluid damper. Variable orifice dampers been developed and studied by [53] [54] [55] and Kajima corporation in Japan. The developement of MR fluid dampers that utilize MR fluids to provide controllable damping forces is perhaps the most important development in semi-active devices. These devices overcome many of the expenses and technical difficulties associated with semi-active devices previously considered. For improving the scalability of MR fluid technology to devices of appropriate sizes for civil engineering applications, a large-scale 20-ton MR fluid damper has been designed and built [56]. The on/off range of the damper is well over the design specification of 10 [56]. Through simulations and laboratory model experiments, MR dampers have been shown to significantly outperform comparable passive damping configurations, while requiring only a fraction of the input power needed by the active controller [57] [58] [59] [60] [61] [62] [63] [65] [66] [67] [68] [69] [70].

Large scale resettable semi-active stiffness damper (RSASD) has been developed and successfully tested by researchers at University of California Irvine [71]. A pioneering concept of variable-stiffness device that Professor Kobori and his group has been implemented in a full-scale variable-orifice device, using the on-off mode, in a variable stiffness structual system (AVS) for semiactive control of the Kajima Research Institute building. Although a variable orifice damper can be used for producing variable stiffness in an on-off mode, it cannot vary stiffness continuously between different stiffness states. Nagarajaiah et al. [72] has developed a semi-active continuously and independently variable stiffness device (SAIVS); this is a scalable mechanical device. The SAIVS device can vary the stiffness continuously and smoothly. They [72] have shown the effectiveness of SAIVS device in a scaled structural model by varying the stiffness smoothly and producing a non-resonant system. Recently they have also developed a new variable fluid spring and damper in collaboration with Taylor devices [73].

Many researchers have studied the advantages and effectiveness of tuned mass dampers (TMD) and multiple tuned mass dampers (MTMD). The TMD is very sensitive to tuning frequency ratio, even when optimally designed. The MTMD can overcome this limitation of the TMD; however, the MTMD cannot be retuned in real time, thus it is not adaptable. Further, space constraints can limit the location of a large number of TMDs. The TMDs with adjustable damping offer additional advantages over TMDs. As an attractive alternative, a semi-active tuned mass damper (STMD), with variable stiffness, that has the distinct advantage of continuously retuning its frequency in real time thus making it robust to changes in building stiffness and damping, has been developed at Rice University [74][75] using the SAIVS device; they have shown its effectiveness analytically and experimentally. The variation of stiffness of the STMD is based on the estimation of the instantaneous frequency and time frequency controllers [74][75][76]. STMDs can also be based on (1) controllable tuned sloshing dampers (CTSD), and (2) controllable tuned liquid column dampers (CTLCD). Tuned sloshing damper (TSD) uses the liquid sloshing in a tank to add damping to the structure, while in a TLCD the moving mass is a column of liquid, which is driven by the vibrations of the structure. Because these systems have a fixed design, they are not as effective for a wide variety of loading conditions, and researchers are looking to improve their effectiveness in reducing structural responses. Researchers at Univ. of Notre Dame [77] have studied semi-active CTLCD devices based on a TLCD with a variable orifice.

Various semi-active devices have been proposed which utilize forces generated by surface friction to dissipate vibratory energy in a structural system. Recently, variable friction systems have been studied at City University in New York [78] [79] [80] for seismic response reduction of buildings. In addition they have proposed an analytical model and a corresponding pulse filter in frequency domain for pulse components observed in near-field ground motions. The pulse model has been used to investigate the effectiveness of passive energy dissipation systems in time domain [81][82][83]. Researchers at Missouri Institute of Technology [84] have integrated piezoelectric actuators into a friction device to make the device semi-active in responding to structural responses. For higher efficiency, a next-generation device with multiple friction surfaces in parallel has been proposed by Chen et al. [85], making piezoelectric friction dampers. Researchers at Georgia Tech [86] and University of Maryland have developed SMA based dampers [22] suitable for bridges. Zhang et al. [22] studied superelastic Cu-Al-Be alloy, which exhibits excellent superelastic behavior (energy dissipation and self-centering) in a wide temperature range from -65C to 180C. This smart material proves to be very promising for use as passive damping device for seismic protection of highway bridges in cold regions

Scruggs and Iwan [87] proposed a regenerative force actuation (RFA) network. In contrast to conventional semi-active system, the RFA networks have the capability of storing (e.g. in a flywheel) at least a fraction of the energy they remove from the structure, and then re-injecting that energy back into the structural system at a later time. When multiple regenerative actuators are distributed throughout a structure, the network can facilitate ”sharing” of power between devices.

Full Scale Applications The first full-scale implementation of semiactive control in the USA was conducted on the Walnut Creek Bridge on interstate highway I-35 to demonstrate variable damper technology [51]. This experiment constitutes the only full-scale implementation of semiactive control in the USA. In 2001, the first full-scale implementation of MR dampers for civil engineering applications was achieved. The Nihon-Kagaku-Miraikan, the Tokyo National Museum of Emerging Science and Innovation, has two 30-ton MR Fluid dampers installed between the 3rd and 5th floors [49]. The dampers were built by Sanwa Tekki using the Lord Corporation MR fluid. Retrofitted with stay-cable dampers, the Dongting Lake Bridge in Hunan, China, constitutes the first full-scale implementation of MR dampers for bridge structures [49]. Long steel cables, such as that used in cable-stayed bridges and other structures, are prone to vibration induced by the structure to which they are connected and by weather conditions, particularly the combination of wind and rain, that may cause cable galloping. The extremely low damping inherent in such cables, typically on the order of a fraction of a percent, is insufficient to eliminate this vibration, resulting in a life reduction for the cable and connection due to fatigue and/or breakdown of corrosion protection. Recently, MR dampers are also employed in the Binzhou Yellow River Bridge in China to reduce the cable vibration. In 2000, the world’s first smart base isolated building was constructed at the Keio University School of Science and Technology in Japan. This office and laboratory building employs variable orifice dampers in parallel with traditional damping mechanisms. Recently, 40-ton MR fluid dampers were installed in a residential building in Japan along with laminated rubber bearings, lead dampers, and oil dampers to provide the best seismic protection [88]. The implementation has been the result of extensive research about the effectiveness of passive base isolation systems for protecting structures against near-source, high-velocity, long period pulse earthquakes, and possible alternatives. A possible approach is the use of a combination of the passive base isolation system with active or semi-active control devices. Since passive base isolation systems usually are nonlinear, hybrid control systems are essentially nonlinear in nature, and various control methods have been studied [55] [89] [90]. Hybrid control systems are also referred to as smart base isolation systems when variable dampers and stiffness devices are used at the isolation level. Several researchers have studied smart base isolation systems [53] [60] [61] [91] and shown their effectiveness for near-field earthquakes [64] [92] [93] [94].

Hybrid Simulation of Controlled Structures As described earlier Magneto-Rheological (MR) fluid dampers have been identified as a particularly promising type of semiactive control device for hazard mitigation in civil engineering structures. Large-scale experimental testing is important to verify the performance of MR fluid dampers for seismic protection of civil structures. Real-time hybrid testing, where only the critical components of the system are physically tested while the rest of the structure is simulated can provide a cost-effective means for large-scale testing of semiactive controlled structures. Real-time hybrid simulation for three large-scale 200 kN MR fluid dampers was conducted as part of a NSF-funded pre-NEESR project at the University of Colorado at Boulder (CU) shared-use Fast Hybrid Test (FHT) to conduct real time hybrid testing within the Network for Earthquake Engineering Simulation (NEES) [95] [96].

BENCHMARK PROBLEMS Recently well-defined analytical benchmark problems [97] [98] [99] have been developed for studying response control strategies for building and bridge structures subjected to seismic and wind excitations, by a broad consensus effort of the ASCE structural control committee. The goal of this effort was to develop benchmark models to provide systematic and standardized means by which competing control strategies, including devices, algorithms, sensors, etc., can be evaluated. Carefully defined analytical benchmark problems are excellent alternatives to expensive experimental benchmark test structures. Details of the 76 story wind-excited benchmark problem has been presented by [100]. Due to the effectiveness of the fixed base building benchmark effort, the ASCE structural control committee voted to develop a new smart base isolated benchmark problem. Narasimhan, et al. [101] have developed the smart base isolated benchmark problem. A special issue of the journal of structural control and health monitoring (JSCHM) was published on the smart base isolated benchmark problem phase I with 15 papers focusing on controllers for linear isolate systems [98] and a special issue is in press in the JSCHM for phase II with 9 papers focusing on controllers for nonlinear isolated system. A new highway bridge benchmark problem has been developed by Agarawal et al. [102][103]. This benchmark problem is based on the newly constructed 91/5 highway over-crossing in Southern California. The goal of this effort is to develop a standardized model of a highway bridge so that competing control strategies, including devices, algorithms and sensors, can be evaluated comparatively. Benchmark problems developed to-date are analytical representations of large-scale civil engineering structures. In order to resolve various practical issues and demonstrate capabilities of various control algorithms/devices, Loh et al [104] have proposed two large-scale experimental building benchmark problems. Detailed information on this benchmark problem will be provided in near future.

CONCLUSIONS In conclusion while this paper attempts to summarize the ongoing U.S. research in the area of structural health monitoring and control, it is by no means complete. The U.S. Panel has attempted to summarize the activities. There are many more research findings that could not presented in this paper due to space limitations, and the interested reader is referred to the JSCHM the premier journal of the International Association of Structural Control and Health Monitoring.

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