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# SMART STRUCTURES AND BUILDING AUTOMATION IN THE 21$^{ST}$ CENTURY

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**ABSTRACT**

Building automation has become increasingly common and advanced in the past two decades. There is also a trend toward design of large and significant buildings such as highrise buildings with unusual configurations. In this Keynote Lecture it is argued that the next big step in building automation will be development of smart structures and its integration with an automated building environment. The author will present a new vision and way of designing and managing building and bridge structures for the 21$^{st}$ century. In this vision strategically placed sensors monitor the health of the smart structure under different loading conditions such as winds and earthquakes and properly designed actuators apply internal forces to compensate for the destructive forces of the nature. A number of key computing and information technologies are presented to achieve the goal of intelligent building and bridge structures.

**KEYWORDS**

Building automation, health monitoring of structures, smart structures

## INTRODUCTION

Building automation has become increasingly common and advanced in the past two decades. There is also a trend toward design of large and significant buildings such as highrise buildings with unusual configurations. Aesthetics is becoming increasingly more important in design of landmark buildings. Owners are no longer content with the old forms and are demanding structures that make a statement. In this Keynote Lecture it is argued that the next big step in building automation will be development of smart structures and its integration with an automated building environment. The author will present a new vision and way of designing and managing building and bridge structures for the 21st century. In this vision strategically placed sensors monitor the health of the smart structure under different loading conditions such as winds and earthquakes and properly designed actuators apply internal forces to compensate for the destructive forces of the nature.

A number of key computing and information technologies are presented to achieve the goal of intelligent building and bridge structures. They include active and hybrid vibration control, wavelets, chaos theory, dynamic neural networks, and genetic algorithm. Examples of recent research in the areas of vibration control and health monitoring of smart structures performed by the author and his research associates are presented.

## ACTIVE AND HYBRID CONTOL OF SMART STRUCTURES

Classical feedback control algorithms such as the Linear Quadratic Regulator (LQR) and Linear Quadratic Gaussian (LQG) algorithms (Adeli and Saleh, 1997, 1999; Saleh and Adeli, 1997) have been used for structural control problems over the past three decades. These algorithms are among the most popular optimal feedback control algorithms mainly due to their simplicity and ease of implementation. Even though they can be used to reduce vibrations, they suffer from a number of fundamental shortcomings such as being susceptible to parameter uncertainty and modeling error (Prakah-Asante and Craig, 1994) and failing to suppress the vibrations when frequency of the external disturbance differs even slightly from the natural frequencies of the structure. Kim and Adeli (2004) developed novel control algorithms to overcome the limitations of classical feedback control algorithms. They present a hybrid feedback- Least Mean Square (LMS) algorithm for control of structures through integration of a feedback control algorithm such as the LQR or LQG algorithm and the filtered-x LMS algorithm. It is shown that the hybrid feedback-LMS algorithm minimizes vibrations over the entire frequency range and thus is less susceptible to modeling error and inherently more stable.

Wavelet analysis is a transformation method in which the original signal is transformed into and represented in a different domain that is more amenable to analysis and processing (Adeli and Karim, 2005). In recent years, the senior author and his associates have advanced the applications of wavelets in various engineering fields such as transportation engineering (Adeli and Samant 2000, Samant and Adeli 2000, 2001, Adeli and Karim 2000, Karim and Adeli 2002a&b, Ghosh-Dastidar and Adeli, 2003, Adeli and Ghosh-Dastidar, 2004, Jiang and Adeli, 2004, Adeli and Karim, 2005, Ghosh-Dastidar and Adeli, 2006; seismology and earthquake engineering (Zhou and Adeli 2003a&b; Sirca and Adeli 2004); structural engineering (Kim and Adeli, 2004, 2005a, Jiang and Adeli, 2005, Adeli and Jiang, 2006); and biomedical engineering (Adeli et al. 2003; Adeli and Ghosh-Dastidar 2007).

Adeli and Kim (2004) present a new wavelet-hybrid feedback LMS algorithm for robust control of civil structures through adroit integration of a feedback control algorithm such as the LQR or LQG algorithm, the filtered-x Least Mean Square (LMS) algorithm, and wavelets. The new wavelet-based control algorithm has the following advantages: a) It includes the external excitation term in its formulation, b) It is capable of suppressing vibrations over a range of input excitation frequencies, c) It is less susceptible to structural modeling approximations and errors than classical feedback algorithms, d) It is effective for control of both steady-state and transient vibrations, and e) It uses wavelet transform for stable updating of the coefficients of the adaptive filter in the control algorithm.

The tuned liquid column damper (TLCD) system was introduced to civil engineers as another type of passive damping system, a special kind of tuned mass damper (TMD) system (Sakai et al. 1989). In a TLCD system the solid mass is replaced by liquid (commonly water) and control forces are based on the motion of a liquid column in a U-tube-like container to counteract the forces acting on the structure. The TLCD system exerts a damping force by passage of the liquid through an orifice (Balendra et al., 1995, Won et al, 1996). It can provide the same level of vibration suppression as a conventional TMD system but with a number of advantages (Kim and Adeli, 2005a, b). If the head loss coefficient in a TLCD system can be changed by a controllable orifice, then the passive damping force is transformed into an active force which controls the response of the structure. The result would be a semi-active TLCD system. By optimally adjusting the head loss coefficient, the semi-active TLCD system can achieve a significant improvement over passive TLCD system (Kim and Adeli, 2005a). Kim and

Adeli (2005a) present a hybrid control system through judicious combination of the semi-active TLCD system with viscous fluid passive damper devices.

Kim and Adeli (2005c) investigate control of irregular highrise building structures under various seismic excitations using a hybrid control system consisting of a passive supplementary damping system and a semi-active tuned liquid column damper (TLCD) system. The wavelet-based optimal control algorithm is applied to find the optimum control forces. Simulation results for control of two multistory moment-resisting space steel structures with vertical and plan irregularities show clearly that the hybrid damper-TLCD control system significantly reduces responses of irregular buildings subjected to various earthquake ground motions as well as increases reliability and maximum operability during power failure.

## NONLINEAR CONTROL OF STRUCTURES

Recently, Jiang and Adeli (2008a) presented a new nonlinear control model for active control of three dimensional highrise building structures under extreme dynamic loadings. Both material and geometrical nonlinearities are considered in modelling the structural response. A dynamic fuzzy WNN is developed as a fuzzy wavelet neuroemulator to predict structural responses from the immediate past structural responses and actuator dynamics. A floating-point genetic algorithm is developed for finding the optimal control forces for active nonlinear control of building structures using the dynamic fuzzy wavelet neuroemulators (Jiang and Adeli 2008b). A highrise steel building structure with vertical irregularity is used to validate the new neuro-genetic control algorithm under two seismic excitations. Validation results demonstrate that the new control methodology is effective in significantly reducing the response of large irregular building structures subjected to seismic excitations.

## HEALTH MONITORING OF STRUCTURES

Adeli and Jiang (2006) present a dynamic time-delay fuzzy wavelet neural network (WNN) model for nonparametric identification of structures using the nonlinear autoregressive moving average with exogenous inputs approach. The model is based on the integration of four different computing concepts: dynamic time delay neural network, wavelet, fuzzy logic, and the reconstructed state space concept from the chaos theory. Noise in the signals is removed using the discrete wavelet packet transform method. In order to preserve the dynamics of time series, the reconstructed state space concept from the chaos theory is employed to construct the input vector. In addition to denoising, wavelets are employed in combination with two soft computing techniques, neural networks and fuzzy logic, to create a new pattern recognition model to capture the characteristics of the time series sensor data accurately and efficiently. The model is applied to two highrise moment-resisting building structures taking into account their geometric nonlinearities. Validation results demonstrate that the new methodology provides an efficient and accurate tool for nonlinear system identification of high-rising buildings.

Jiang and Adeli (2007) present a nonparametric system identification-based model for damage detection of irregular highrise building structures using the dynamic fuzzy WNN model with an adaptive Levenberg-Marquardt-least squares learning algorithm. The model does not require complete measurements of the dynamic responses of the whole structure. A large structure is divided into a series of sub-structures around a few pre-selected floors where sensors are placed and measurements are made. A new damage evaluation method is proposed based on a power density spectrum method, called *pseudospectrum*. The multiple signal classification (MUSIC) method is employed to compute the pseudospectrum from the structural response time series. The damage detection methodology is validated using the sensed data obtained for a 38-story concrete test model. This research provide an effective tool for real-time health monitoring and nondestructive damage evaluation of both highrise building and bridge structures.

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## BIOSKETCH OF THE KEYNOTE LECTUREER

Hojjat Adeli is Professor of Civil and Environmental Engineering and Geodetic Science at The Ohio State University. He is also the holder of Abba G. Lichtenstein Professorship. He has authored over 420 research and scientific publications in various fields of computer science, engineering, applied mathematics, and medicine since 1976 when he received his Ph.D. from Stanford University. He has authored 11 books including Machine Learning - Neural Networks, Genetic Algorithms, and Fuzzy Systems, Wiley, 1995, Neurocomputing for Design Automation, CRC Press, 1998, Distributed Computer-Aided Engineering, CRC Press, 1999, Control, Optimization, and Smart Structures - High-Performance Bridges and Buildings of the Future, Wiley, 1999, Wavelets in Intelligent Transportation Systems, Wiley, 2005, and Cost Optimization of Structures, Wiley, 2006. He has also edited thirteen books including Knowledge Engineering - Vol. I - Fundamentals and Vol. II -Applications, McGraw-Hill, 1990, Intelligent Information Systems, IEEE Computer Society, 1997, and Historic Bridges: Evaluation, Preservation, and Management, CRC Press, 2008. He is the Founder and Editor-in-Chief of the international research journals Computer-Aided Civil and Infrastructure Engineering, now in 23rd year of publication and Integrated Computer-Aided Engineering, now in 16th year of publication. He is also the Editor-in-Chief of International Journal of Neural Systems. In 1998 he received the Distinguished Scholar Award from The Ohio State University “in recognition of extraordinary accomplishment in research and scholarship”. In 2005, he was elected Honorary Member, American Society of Civil Engineers: "for wide-ranging, exceptional, and pioneering contributions to computing in many civil engineering disciplines and extraordinary leadership in advancing the use of computing and information technologies in civil engineering throughout the world.” In 1996, he received the ASCE Construction Management Award for “For development of ingenious computational and mathematical models in the areas of construction scheduling, resource scheduling, and cost estimation,” In 2007, he received The Ohio State University College of Engineering Peter L. and Clara M. Scott Award for Excellence in Engineering Education “for sustained, exceptional, and multi-faceted contributions to numerous fields including computer-aided engineering, knowledge engineering, computational intelligence, large-scale design optimization, and smart structures with worldwide impact,“ as well as the Charles E. MacQuigg Outstanding Teaching Award.