Assessment of Civil Engineering Structures by Vibration Monitoring

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ABSTRACT

The need for rapid assessment of the state of critical and conventional civil structures such as bridges, control centers, airports, hospitals among many, has been amply demonstrated during recent natural disasters. This paper presents the overall framework of structural damage monitoring systems and summarizes current research efforts in the field. Such systems incorporate a sensing and microprocessing unit, data transmission and acquisition system, and damage diagnostic methods. Current advances in wireless communication, micromachined sensors, global positioning systems, and increased computational power provide the tools for potential new solution to many of the obstacles presented by such systems. Issues of communication, power requirements, data transmission, and damage analysis algorithms are addressed in the paper.

INTRODUCTION

Inspection of existing buildings and bridges after major catastrophic events, such as earthquakes and hurricanes, as well as under normal operating conditions, is often very time consuming and costly because critical members and connections are concealed under cladding

and other architectural surface covers. For critical structures, such as hospitals, fire stations, military control/surveillance centers, major bridges, power stations, and water treatment plants, it is imperative that their health be assessed immediately after a major catastrophic event. Similarly, dissemination of information to emergency response officials on major collapses of structures within minutes after the occurrence of a natural or manmade disaster can result in saved lives and prudent resource allocation. Often such information is delayed due to weather conditions, lack of daylight, or appropriate survey equipment, or inaccessibility to the site due to terrain obstacles. In many instances, impending collapse of a structure may not be visible from the exterior of the structure. During the January 17, 1994 Northridge, California earthquake several structures that were weakened (but undetected) by the main shock collapsed when a major aftershock occurred. Thus, identification of critically damaged structures will enable timely evacuation of occupants.

While sensing and health monitoring technology has been widely developed and used in the aerospace, automotive and defense industry, it is only recently that attention has focused on civil structures. The deterioration of our infrastructure has pointed to the need for health monitoring of structures under everyday loads. During the last decade considerable theoretical and experimental advances have been made in structural control. In parallel, attempts have been made to design general earthquake damage monitoring systems. For example, conceptual models have been developed for the sensor location, signal transmission, and central processing of information for simple structural systems (e.g., Chang et al., 1990; Nee, 1990; Spyrakos et al, 1990; Wu, 1990).

Laboratory and field experimentation with frame structures and bridges have shown promise for identification of system behavior and critical parameter benchmarking (e.g. Lu and Askar, 1990; Agbabian and Masri, 1988; Beliveau and Huston, 1988; Biswas et al., 1989).

This paper presents the overall framework of structural damage monitoring systems and summarizes current research efforts in the field. Such systems incorporate a sensing and microprocessing unit, data transmission and acquisition system, and damage diagnostic methods. Current advances in wireless communication, micromachined sensors, global positioning systems, and increased computational power provide the tools for potential new solution to many of the obstacles presented by such systems. Issues of communication, power requirements, data transmission, and damage analysis algorithms are addressed in the paper.

CONCEPTUAL DESIGN

Structural damage monitoring systems consist of sensors, communication hardware, and data acquisition and processing components that to measure and assess the integrity of a structure. The primary uses of structural monitoring systems are either to determine the long-term "health" of a structure through strength and stiffness deterioration or to identify the damage to a structure caused by an extreme event. Two types of structural monitoring systems can be identified: (1) systems that measure peak response quantities, such as strain, at selected points in a structure and then correlate peak response quantities to long-term structural "health", and (2) systems that employ system identification procedures to estimate the changes in various parameters of a structure for damage determinations. Current structural monitoring systems consider either local damage or global damage parameters.

The conceptual design of the civil structural damage monitoring system is based on a simple hierarchical scheme consisting of three distinct but interrelated levels:

(1) the sensor,
(2) the structure, and
(3) the central monitoring facility.

Figure 1 shows the schematic configuration of the proposed system. The three components of the monitoring system are described as follows.

Over the past two decades numerous new sensors have been invented. The type of sensor to be deployed depends on the physical quantities needed to be measures. For example, measurements of acceleration or strain can be used to

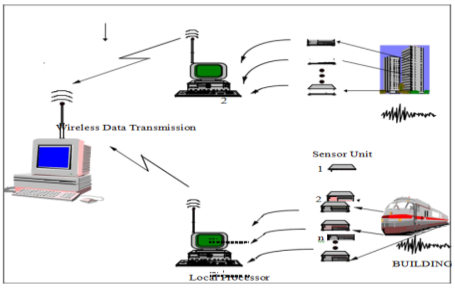

Figure 1. Conceptual Structural Monitoring System.

Data from the sensor unit is transmitted to a data processor. Currently, most sensors provide raw data that has not been processed at the structure site. Site master units typically serve as data collectors but not necessarily as processors. More recently, sensors have been developed that provide partial on site processing and storage of data. Often data processing is performed at locations some distance away from the site. Data transmittal to such locations presently is achieved through telephone communications links.

A well designed sensor system will have a site master processor that provides the primary computational engine and is manager of the structural monitoring system. Functions performed by the site master processor could include: coordination and collection of transmitted sensor data, manipulation and analysis of structure specific information, evaluation and determination of structural damage, and transmission of desired structural damage quantities to a central facility. The data from the individual sensors can either be queued or queried by such a site master processor. Currently available digital data acquisition systems and wireless communication capabilities can facilitate rapid data transmission from the sensors to the site master processor without the need of intrusive and vulnerable wires running through the structure. Several analysis tools can be coded within the site master processor, each enabling determination of properties and performance of the overall structure. Examples include system identification, nonlinear time history analysis, frequency domain analysis, and correlation of measured structure quantities to threshold system parameters. If necessary, the site master processor may query any sensor for more information or to perform some simple local analysis and transmit back the information. Damage thresholds can be established to activate alarms at the central facility. Decision tools for selecting appropriate information for transmission to the central facility can be incorporated as part of the functions of the site master processor. Such functions, however, should be able to be overridden by requests from the central facility.

The central monitoring facility is intended to receive and process damage information from all structures in the monitoring system. The central facility typically monitors structures over a wide region spanning several counties. For example, all hospitals may be connected to a central command post monitored by a local, state or federal agency responsible for emergency operations after the occurrence of a natural, manmade, or technological disaster. Following such a disaster, the information from the site master processor is relayed to the central facility for further processing.

Information housed at the central facility may include structural data in CAD format with sensor locations identified. Graphical interfaces may show the location and degree of damage throughout the structure. The type of structural and sensor/processor data and the analysis and decision tools to be stored in the central monitoring facility need to be clearly defined. For example, for bridges, it may be sufficient to transmit information on the level of damage (e.g., amount of separation at seat joints, formation of hinge in a column, amount of settlement at the footing or abutment, etc.) or residual functionality of the structure. For fire stations or hospitals, it is important to provide global as well as local information. Local information can include specific structural components, their materials, exits, sprinkler location, intensive care areas, etc. Such information may be preprocessed and warehoused at the central monitor to be retrieved upon request as information arrives from the site master processor. Retrieval may be automatic or initiated by an operator. Additional analysis and computational tools can be coded in the central monitoring unit. Furthermore, a warning system can be designed to signal the occurrence of a catastrophic failure which may result in possible deaths and injuries. Such a system should have the capability to be turned on by an operator as needed or desired to perform interim system testing or structural integrity identification.

Key issues to be resolved include (a) design and development of reliable hardware for two-way transmission of multitudes of signals over large distances; (b) development of algorithms for damage, loss, and casualty assessment to be hard-coded at the site master processor, (c) development of damage visualization algorithms, (d) development of decision analysis tools as required by key emergency response personnel. Currently, there are no central monitoring systems

in existence for commercial use. Utility companies and emergency response organizations in the United

States are presently considering the design and implementation of such systems.

SENSORS, MICROPROCESSORS AND DATA COMMUNICATION

Improvements in both sensor and electronic technology make it possible to create small self-contained units that are able to sense their environment and transmit important observations to a remote site using wireless communication links. Distributing a large number of these units on a structure and allowing them to communicate with each other can create a powerful, and unattended distributed monitoring system that has a variety of applications. Such applications may include structure monitoring, public safety, border monitoring, military uses, and basic science applications. Before such systems can be built, there are many technical issues to be addressed in the areas of advanced sensor technology, power-efficient radio systems, low-power computing, and packaging. For example, if battery-powered systems are to provide long fetimes in the field (several years), low power dissipation is a critical issue. Several of these issues are discussed as follows.

SENSOR TECHNOLOGY

Through the widespread and increasing availability of high-performance micromachined and conventional miniaturized sensors, it is now possible to construct and efficiently distribute sensor systems with multi-modal capabilities, low power small size and low cost. Typically, sensors for strain, tilt, corrosion, and seismic phenomena are required. Issues that ultimately may determine the actual sensor suite for a given design include: desired sensing modalities, availability of suitable sensors with appropriate robustness for the application environment, and power, volume/weight, cost and data rate constraints.

The sensors described in this paper are representative examples of “off-the-shelf” (primarily commercially, but in some instances from proven academic research projects) sensors that can be selected for each sensing modality. There is clear potential to utilize silicon micromachined or “MEMS” sensor technology for ultimately scaling down the sizes of the modules.

The most widely used sensors for structural monitoring are the accelerometers. There are a wide variety of accelerometers that satisfy requirements of measurement sensitivity (<10mg/Hz$^{1/2}$), have small footprint and are lightweight. While accelerometers are widely used as tiltmeters, considerably improved measurements can be obtained from silicon micromachined electrolytic inclinometers (tiltmeters). Currently available tiltmeters can provide angular resolution about two axes up to 1 milliradian over ranges of +/-10 degrees. These sensors are particularly useful for

measurement of vibration effects and permanent deformations in structural members.

Crack monitoring, strain measurements, and corrosion determination can be achieved through local diagnostic sensors. Methods to measure and quantify cracks include acoustic emission, ultrasonic detection, magnetic resonance, and a variety of optical and visual techniques. While these methods have their strong points, each arequires either constant monitoring (acustic and ultrasonic), substantial and expensive hardware (magnetic resonance and optical), or physical access to the location of interest (visual inspection).

For local strain monitoring large area strain gages (e.g., metal foil or doped silicon strain gages) can be used for member strain measurement and can undergo cyclic strains compatible with structural steel vibration behavior. Such strain gages, however, need to be placed at critical locations requiring that these locations be identified prior to placement. The strain measurements can provide benchmarks for a strain based mode shape algorithms or can serve as input to local joint hysteretic analysis.

For a particular application, the sensors and a custom mixed-signal interface chip can be combined with networking, power and packaging hardware. While certain aspects of the sensor module can be heavily affected by the intended scenario (i.e. packaging and exact choices of sensors), the major performance and power optimized blocks (i.e. data acquisition, signal processing, data compression, and telecommunications) may not require customization. A robust sensor system should be designed on these key system building.

Typical piezoresistive seismic sensors/accelerometers are already extremely low power and have no power-up latency. This latter feature allows them to be energized only at the exact instant of signal sampling, allowing the power consumption of already low-power devices to be minimized. Clearly this approach must be evaluated for a given data rate to ensure that energy lost charging and discharging parasitic capacitances does not outweigh that saved by time slicing. Other types of sensors that can be considered include resistive large dimension strain gages and these utilizing eddy currents techniques to evaluate flows and cracks in materials. Both of these sensors require extremely low power, however, the efficient generation of an AC signal from the battery DC power for eddy current based sensors needs to be addressed.

As explained below, the actual operating duty cycles of all sensors needs to be carefully minimized to extend battery life. Some sensors, such as acoustic and seismic sensors can be sampled continuously (but at programmable reduced data rates) to provide "triggering" functions for the more power-hungry sensors. Even the sensors that are sampled "continuously" should be powered only during the sampling intervals.

Critical to the successful use of such a distributed sensor network is the ability to efficiently and robustly transmit this multi-modal information to receiving sites. Clearly, the transmission protocols must be extremely flexible, since the raw bandwidth requirements of each type of sensor vary over several orders of magnitude and the sensor of most interest at a particular time may not be predictable in advance.

The objective of the sensor protocol is to provide intelligent and autonomous sensor polling with a pre-programmed background routine and capability for any sensor to be interrogated if necessary. The bulk of the operating time of a sensor module should be spent in a low power "background mode." Background mode entails scanning some sensors at a low duty cycle appropriate for each. Readings, such as humidity, have typical time constants of hours, while accelerometers need to be monitored more frequently. For sensors such as the latter case, higher data bandwidths are required, but only if an event of interest occurs. For this type of "bursty" sensor, low-power polling can be obtained using hardware "trigger" circuits that would "wake up" sampling circuits when a programmable signal threshold is exceeded. For this purpose, simple circuits such as a clocked peak-hold circuit and comparator per analog sensor can be employed, generating a hardware interrupt and a burst of analog-to-digital conversion to a buffer memory when activated. The data thus captured can be relayed out through the network and if deemed necessary, the sending module could be reprogrammed to focus on, and continuously transmit from, the triggered sensor(s).

Sophisticated signal processing to provide for local intelligence on each sensor module is critical in reducing overall data bandwidth, thereby the required transmit power. Previous research has indicated that complicated signal processing tasks involving more than 100 million operations per second, such as required in real-time video compression and image pattern recognition, can be performed at a power level of approximately 1 mW. Special-purpose signal processing chips can be integrated into sensor modules with on-board computation capability can greatly enhance sensing accuracy and facilitate local intelligence for collective decision-making without involving high-bandwidth or long-distance data communication.

POWER MANAGEMENT OF DATA TRANSFERS

In recent years wireless technology has revolutionized digital communications. This technology represents a unique opportunity to greatly improve the data transmission of variety of sensed data within the local sensor network and from the sensor network to the central monitoring station. Implementation of this technology requires consideration of transmission distances, signal penetration through various materials and signal power.

In wireless RF transmission, for a minimum usable receiver power at -110 dB and a distance of 100 feet, the transmit power at a carrier frequency of a few 100 MHz (chosen as a compromise between penetration capability and noise immunity) can be as low as 1 mW. Considering the efficiency of the transmitter electronics, the active power of the transmitter can be a few mW. This low level of transmit power is possible only if strictly local communication is used to maintain network connectivity.

Basically there are two kinds of signals transmitted within such wireless network. One is the synchronization signal for status report at a constant rate. The other is the bursty data signal which may require orders of magnitude higher bandwidth in reaction to detected signals. The design of the transceiver needs to support both kinds of signals using minimal p• wer.

Since the receiver for the high-bandwidth signals is only turned on when the unit is told to listen, which is assumed to be an infrequent event, the dominant power drain is the power needed for the status signals. The difference in duty cycle between the transmitter and receiver means that it may be beneficial to increase the transmit power if that enables a reduction in the receiver power. This component of the system requires considerable further exploration and research.

STRUCTURAL SYSTEM AND COMPONENT DAMAGE EVALUATION METHODS

Diagnosis of damage in structural systems requires the identification of the location and type of damage and quantification of the degree of damage. Damage detection methods currently in use rely on visual inspection or on localized measurements. Measurement based methods are still very much at the experimental or research state with little if any practical deployment. Methods currently used include acoustic or ultrasonic measurements, magnetic field change measurements, radiograph, eddy current and thermal field change detection techniques. Doebling et al. (1996) present a comprehensive literature review of damage identification and health monitoring methods for structural and mechanical systems. Their review focuses on methods based on vibration measurements and detection based on changes in vibration characteristics.

Rytter (1993) defines four stages of damage monitoring:

(1) Determination that damage is present in the structure;

(2) Determination of the geometric location of the damage;

(3) Quantification of the severity of the damage;

(4) Prediction of the remaining service life of the structure.

These stages of damage monitoring my lead to different types of sensor requirements or multi-sensor systems. Similarly, damage algorithms will vary depending on the type of monitoring desired. For example, if stage one information is needed, then sparse vibration measurements may be sufficient to ascertain the existence of damage somewhere in the structure. Identification of the location of damage may require considerably richer sensor network and perhaps sensors that provide more robust local information. In order to determine the degree of damage, in addition to the sensor selection, efficient and robust damage algorithms are need. Prediction of remaining service life is typically based on fatigue and fracture measurements and may require different sensors and mathematical tools leading to the estimation of remaining life or assessment of compliance with design specification. The challenge is in developing systems that can respond to all four stages of damage monitoring.

A robust, efficient, and economical damage detection system critically depends on the information extracted from the sensors. Due to economic constraints, it is impossible to completely instrument civil structures for damage monitoring. Therefore, algorithms and methodologies that address the issue of limited instrumentation and its effect on resolution and accuracy in damage diagnosis are paramount to the application of a damage monitoring systems. There are numerous studies regarding optimum sensor placement. Most methods are based on maximizing the trace or determinant (or minimizing the condition number) of the Fisher Information matrix which is expressed as a function of selected parameters corresponding to the objective function. One example is the optimum sensor location (OSL) algorithm proposed by Udwadia (1994) that minimizes the covariance error between the structural parameters that are to be identified and their estimate from the limited measurements. An alternative approach is the effective independence method (Efi) presented by Kammer (1992) which determines the final sensor configuration by selecting sensor location by iteratively removing sensor locations that do not contribute significantly to the linear independence of the mathematical mode shapes. The final sensor location distribution is such that the covariance matrix between the displacement vector in modal coordinates and the modal displacements are minimized. A combination of these methods have been considered by Hemez (1993) and an energy matrix rank optimization methods (EMRO) are proposed by Lim (1991). The EMRO method selects the optimal sensor location by maximizing the measured strain energy stored at the sensor locations.

There are many outstanding issues in the selection of sensor locations. Currently available sensor location algorithms pertain to linear multi-degree systems and are applicable primarily to space trusses. Thus there is a need for the development of optimal sensor location methods for nonlinear multi-degree frame systems.

LOCAL DAMAGE DIAGNOSIS

In order to determine local damage, it is first necessary to identify the critical damage modes in structural members (e.g., local flange or web buckling of steel columns, beams and braces; fracture at welded or bolted steel beam to column connections and brace to joint connections; and yielding of beam or column sections). The assessment of the different damage modes requires different types of sensors and sensor locations. For example, yielding and local buckling is typically associated with large strains and thus can be diagnosed by monitoring strains at critical locations. Evaluation of fractures at critical location in members in existing structures poses a more difficult problem. Provided that appropriate sensors can be placed at critical location of members, algorithms that determine the level of damage can be developed for a component based damage index or for benchmark values for specific damage parameters. Examples of cumulative damage indices include those proposed by Krawinkler (1983) for steel and Park and Ang (1985) for concrete.

It has become apparent with recent extreme natural events, that fracture and extensive cracking at welded and bolted joints is one the most pervasive mode of failure in steel structures. Shear cracks and failure from under-strength of concrete members also are leading causes of damage and failure of concrete structures. Sensors, such as those based on acoustic or fiber-optic (used with concrete structures) measurements are impractical particularly for steel structures since these sensors, if imbedded prior to welding, will be damaged by the welding process. Eddy current inspection methods, however, have been shown to be particularly effective in the detection of cracks, their positions and, through calibration, their dimensions. They have been used in the aerospace industry for material flaw detection and component specification inspections.

STRUCTURAL SYSTEM DAMAGE METHODS

The dynamic behavior of structural systems is governed by the properties of the structural members (beams, columns, braces) and their connections (rigid, semi-rigid, etc.). Damage to structural members and joints has a direct effect on the dynamic properties of the overall system. Damage detection methods that have been proposed include the “classical” approach (West, 1988; Lieven, 1988), the eigenstructure assignment approach (Minas, 1988; Zimmerman, 1990), the optimal update method (Baruch, 1984; Kabe, 1985), the design sensitivity method (Hemez, 1993; Flanigan, 1987; Ojalvo, 1989), the rank perturbation system (Zimmerman, 1992; Mith, 1990), the statistical parameter identification method (Beck, 1994) and the neural network applications (Elkordy, 1994; Wu, 1992). Analytical methods for structural dynamic property identification are typically divided into time domain and frequency domain techniques. System identification methods are further divided into linear and nonlinear methods. The goal of these techniques is to evaluate the dynamic structural characteristics, such as stiffness, damping, structural period, and mode shapes, and monitor changes in their values or signatures as extreme dynamic loads are applied to the structure. Changes in modal parameters alone, such as natural frequencies and eigen-mode shapes have shown not be robust estimators of structural damage (Loh, 1995). Story drifts, large rotations, and shear force, and strain distributions can be benchmarked to establish performance criteria and show promise as reliable indicators of structural damage.

Earthquakes, hurricanes and tornadoes impose random and extreme loads on structures, thus the response of the structure is also random and usually nonlinear. Thus, the nonlinear behavior of the structural components needs to be considered in these algorithms. Furthermore, different damage algorithms are typically required for long term health monitoring and for damage detection after a catastrophic event.

Among the many methods for long term health monitoring are the methods that estimate changes in structural frequencies, mode shape curvatures or strain mode shape changes, matrix update methods which measure changes in mass, stiffness and damping matrices, and hybrid matrix update methods. Doebling et al. (1996) provide extensive discussion on the advantages and disadvantages of these methods. For extreme event damage monitoring, as mentioned previously, nonlinear methods are required. Although methods have been developed for nonlinear components, treatment of nonlinear systems has been considered only to a limited extent (e.g., Loh, 1995; Masri et al., 1987). Many challenges remain for structural parameter identification, damage detection, location detection and damage assessment of nonlinear structural systems. These challenges will be the subject of future research studies.

CONCLUSIONS:

Smart materials/sensors are a new development with enormous potential for SHM of civil engineering structures. Some of them are currently being applied in the field, while others are being evaluated under laboratory conditions.

FOS is versatile sensors for SHM applications in civil engineering. Various applications of FOS in civil engineering structures, such as monitoring of strain, displacement, vibration, cracks, corrosion, and chloride ion concentration, have been developed. In particular, field tests reported on bridges, hydroelectric projects, and some civil buildings have been found to be effective. FOS can work in a harsh natural environment, and have large sensing scope, joining with low transmission loss, an electromagnetic interference and distributed sensing, and so they are advantageous to apply for SHM of civil engineering structures. However, the long-term sensing ability of FOS under field experimental conditions due to aging has not been fully established, and needs to be investigated further. They are fragile in some configurations, and the damage is difficult to repair when embedded. The optical connection parts, which connect the embedded optical fiber with the outer data recording system, are also weak elements of the FOS system. Field examples using FOS to detect defects and damages have not yet been fully investigated and reported.

Piezoelectric sensors can be used as an active sensing technology in the SHM of civil engineering structures based on electrical impedance and elastic wave methods. The impedance method depends on the self-sensing actuators concept. It is a qualitative method. Elastic wave-based approaches can detect larger areas of damage than the impedance-based method, and this method can take advantage of additional information arising from the wave propagation to identify damages. However, further studies have to be carried out to verify the feasibility of this method to detect various defects in real concrete structures and reinforced concrete structures.

Self-diagnosing fiber reinforced composites are also available as sensors and over a very simple technology for the SHM of civil engineering structures. One of the most obvious advantages of this type of smart materials is that they work as both structural materials and sensing materials. Laboratory studies have shown that they have the abilities to monitor their own strain, damage and temperature. CPGFRP and HCFRP have better sensitivity than CFGFRP. However, the practical applications of this type of smart materials in civil engineering structures are yet to be developed.

Moss can generate different guided wave modes by simply changing the coil or magnet geometry. They can work without any couplets. Guided waves have strong potentials for structural health monitoring because of their long-distance inspection capability. However, it is only suitable for ferromagnetic materials. Relatively low ultrasonic energy with low signal to noise ratio can be transmitted.

SHM system must possess the comprehensive abilities to detect positions and severity of damages. However, until now lots of studies about applications of smart sensors/smart materials in SHM of civil engineering are related to the basic sensing abilities of smart sensors. That is, some damages within structures can be monitored directly using data from sensors, while others can only be detected indirectly through special diagnostic methods. Important civil engineering structures are usually very large. So, many sensors are equipped to make structures sense their health conditions. Wireless transmission and processing the data before trans-mission will be a useful method to solve the problem of bulk data management in the practical SHM system. And SHM of the practical civil engineering structures will greatly depend on diagnostic algorithms such as inverse problem analysis, artificial neural network, and the expert system. So, real SHM system for civil engineering is the integration of smart sensors/smart materials, data transmission, and advanced diagnostic methods.

ACKNOWLEDMENTS

The authors would like to express their gratitude to the National Science Foundation for their support through Grant CMS - 9526102.

REFERENCES

1. Agbabian, M.S. et. al. (1991). "System Identification Approach to Detection of Structural Changes, *Journal Engineering Mechanics, ASCE,* 117 (2), 370-390.

2. Agbabian, M.S., and Masri, S.F., (eds.), (1988). *Proc. Int. Workshop on Nondestructive Evaluation for Performance of Civil Structures*, Univ. of Southern California.

3. Baruch, M., 1994. “Method of Reference Basis for Identification of Linear Dynamic Systems”, *AIAA Journal*, **22**, 561-564.

4. Beliveau, J.G., and Huston, D. (1988). "Modal Testing of Cable-stayed Pedestrian Bridge." *Proc. Int. Workshop on Nondestructive Evaluation for Performance of Civil. Structures*. Univ. of Southern California, 193-202

5. Biswas, M., Pandey, A.K., and Samman, M.M. (1989). "Diagnostic experimental spectral/Modal analysis of a highway bridge." *Int. J. Analytical and Experimental Modal Analysis*, 5(1), 33-42.

6. Doebling, S. Farrar, C., Prime, M., and Shevits, D., 1996. "Damage Identification and Health Monitoring of Structural and Mechanical Systems from Changes in Their Vibration Characteristics: A Literature Review", Los Alamos National Laboratory Report No. LA-13070-MS, Los Alamos, New Mexico 87545

7. Elkordy, M.F. et al., 1994. "Application of Neural Networks in Vibrational Signature Analysis", *Journal of Engineering Mechanics*, *120*(2).

8. Flanigan, C. C., 1987. "Test/Analysis Correlation Using Design Sensitivity and Optimization", *Aerospace Technology Conference and Exposition*, SAE Paper No. 871743, Long Beach, CA.

9. Hemez, F. M., 1993. "Theoretical and Experimental Correlation between Finite Element Models and Modal Tests in the Context of large Flexible Space Structures", Ph. D. Dissertation, University of Colorado.

10. Kabe, A. M., 1985. "Stiffness Matrix Adjustment Using Mode Data", *AIAA*, **23**(9), 1431-1436.

11. Kammer, D. C., 1992. "Sensor Placement for On Orbit Modal Identification and Correlation of Large Space Structures", *AIAA Journal of Guidance, Control and Dynamics*, **14**(2),251-259.

12. Lieven, N.A.J., and Ewing, D.J., 1988. "Spatial Correlation Mode Shapes, The Coordinated Modal Assurance Criterion (COMAC)", *Proc. 6th IMAC*, 690-695.

13. Lim, T. W., 1991. "Structural Damage Detection Using Modal Test Data", *AIAA Journal*, **29**(12), 2271-2274.

14. Loh, C.H. and Tou, I.C. (1995). "A System Identification Approach to the Detection of Changes in Both Linear and Nonlinear Structural Parameters, *International Journal Earthquake Engineering and Structural Dynamics*, 24, 85-97.

15. Masri, S., et al., 1987. "Identification of Nonlinear Vibrating Structures, Part 1 and 2", *Journal of Applied Mechanics*, **54**.

16. Minas, C. and Inman, C. , 1988. "Correcting Finite Element Models with Measured Modal Results Using Eigenstructure Assignment Methods", *Proc. 6th IMAC*, 583-587.

17. Oljavo, I.U. et al., 1989. "PAREDYN-A Parameter Refinement Computer Code for Structural Dynmic Models", *UJMA*, 5(1), 43-49.

18. Rytter, A., 1993. "Vibration Based Inspection of Civil Engineering Structures", Ph. D. Dissertation, Department of building Technology and Structural Engineering, Aalborg University, Denmark.

19. Udwadia, F. E., 1994. "Methodology for Optimum Sensor Locations for Parameteric Identification in Dynamic Systems", *Journal of*

Engineering Mechanics, **120**(2).

20. West, W., 1988. "Structural Fault Detection of a Light Aircraft Structure Using Modal Technology", *JSC Loads and Structural Dynamics Branch Report*, April.

21. Wu, X. Ghaboussi, J. and Garrett, J.H., 1992. "Use of Neural Networks in Detection of Structural Damage", *Computers and Structures*, **42**(4), 649-659.

22. Yao, G.C. and Lien, N. (1994). "Model Moment Analysis for Damage Diagnosis of Steel Structures", *Proc. 5th US National Conference on Earthquake Engineering*, Chicago, IL.

23. Zimmerman, D. C. ad Widengren, M. 1990. "Correcting Finite Element Models Using a Symmetric Eigenstructure Assignment Technique", *AIAA Journal*, **28**(9), 1670-1676.

24. Zimmerman, D. C. and Smith, S. W. 1992. "Model Refinement and damage Detection For Intelligent Structures", in *Intelligent Structural Systems* (Tzou, H. S., ed.), Kluwer Academic Publish

25.