Vibration Based Methodologies for Damage Assessment of Civil Engineering Structures – An Overview

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Abstract: Damage in the structural elements and systems due to vibrations, stress cycles, corrosion, harsh environment etc., causes serious problems in strength and serviceability. To minimize the deterioration and other effects in the structures, structural health monitoring (SHM) and many smart methods of control in detecting damage for large structures are necessary. SHM has a wide range of techniques for condition and damage assessment of an existing structure. A class of SHM known as vibration based damage detection techniques utilizes changes in the dynamic modal characteristics of the structure like natural frequencies, mode shapes, damping. As these dynamic modal characteristics are directly related to specific physical properties of the structures, measured changes in the modal characteristics can be used to detect and quantify damage. This paper aims in presenting an overview of state-of-the-art of vibration based structural damage detection. Various structural damage detection methods which are based on structural dynamic characteristic parameters are summarized.

Keywords: Structural Health Monitoring, Damage detection techniques, Structural vibration.

1. INTRODUCTION

Structural Health Monitoring must remain in the domain specified in the design at every moment during the life of a structure. Although this can be altered by normal aging, usage, action of environment and by accidental events. Identification and estimation of structural damage will intimate the health of the structure. SHM involves the integration of sensors, response measurements and analysis of measurement data and identification of structural parameters in the structures.

Generally, structural damage detection can be classified as local-damage detection and global-damage detection. Local-damage detection technique uses non-destructive testing and it is mainly used to detect local damage and also in the determination of damage existence. The main advantage of the local damage detection is that it is very effective for small and regular structures. However, for the large and complicated structures it is very difficult to detect damage using local damage detection method.

For detecting damage throughout the whole structure like large, complicated structures, a methodology called global vibration-based structural damage detection method can be used. The basic principle implied in this method is that, for any structure it can be taken as a dynamics system with stiffness, mass and damping. Once some damages emerge in the structure, the structural modal parameters like natural frequency, mode shape and damping will change. Thus, the change of the structural modal parameters can be taken as the signal of early damage occurrence in the structural system.

Recently, many researches are working on the Vibration-based structural damage detection methods. It has become a frontal area because it can solve multitudinous important engineering structures by online and continuous damage detection using vibration-based methods. This paper attempts to provide an all around overview on recent progress and development of this interesting area. The vibration-based structural damage detection is employed in theories and techniques among a broad spectrum of multiple disciplines, such as structural dynamics, artificial intelligence, signal processing and measurement technologies.

In addition, the identification of damage under operational conditions, under environmental excitation, output-only identification, the uncertainty analysis with time domain approach and statistical approach for health monitoring, etc., are also noteworthy fields of study on the plethora of vibration-based structural damage detection studies. Many different types of techniques have
been developed to solve these problems including complete or incomplete measurements, new macro-
parameters for identification, solution algorithms, optimization techniques, etc.

2. LITERATURE REVIEW

Mustafa gul and F.Necati catbas [1] presented a study on statistical pattern recognition methods of
SHM using different laboratory structures. Time series modeling called auto- regressive models, was
used in conjunction with Mahalanobis distance-based outlier detection algorithms to identify
different types of structural changes on different test structures. In this study the methodology was
modified by using random decrement functions to eliminate the effects of the exogenous input with
one specimen of a simply supported steel beam and other structure of a highly redundant steel grid
structure. By simulating various damage conditions it showed that different boundary conditions in the
beam were identified successfully by using the methodology. Also comparative analyses showed
that using Random Decrement (RD) for averaging improves the methodology and a better separation
was obtained during the outlier detection process. The methodology gave successful results for the
grid structure most of the time. However, it was also observed that the methodology did not perform
as successful for some cases, such as the Reduced Stiffness case. The results portrayed that there are
a number of issues to be solved before the methodology can be successfully applied to real-
life structures in an automated SHM system. They are improvement in determining the threshold
value to minimize the false positives and false negatives, Sensitivity analysis should be conducted
to examine the effects of different parameters, the environmental and operational inputs should be
investigated by using experimental methods.

Kung-Chun Lu et.al [2] installed wireless sensors on full scale RC – frame structure with and without
brick walls and they were used to measure system responses during shake table testing in laboratory.
Pattern classification method was adopted to classify the structure as damaged or undamaged
using time series co-efficient. Auto-Regressive moving average model was used to identify the
modal frequencies and mode shapes and to detect the location of damage from the changes in
curvature of mode shapes. Auto-Regressive moving average with exogenous models with
recursive prediction error model is used for obtaining the time varying parameters. Two tier
model damage detection models provided more reliable results for damage detection and this was
compared using the AR-ARX (Auto Regressive
moving average with eXogenous input) model
from ambient vibration response data. Wavelet
analysis was used for seismic response data.

Ramanjaneyulu [3] described the efficacies of
different methods for identification of damage in
structures based on vibration data. Artificial neural
network (ANN) is used detect damage in structures
by the use of changes in natural frequencies
between damaged and undamaged structure. For
demonstrating the applicability, cantilever plates
were considered. The damage was identified and
quantified by minimizing errors between the
measured data and numerical results using genetic
algorithm. When the locations of damage are at
symmetrical locations in a symmetric structures,
the frequency are not much sensitive to structural
damage especially to localized damages having
small magnitudes. The combined objective
function both frequency and Modal Assurance
Criterion (MAC) values is found to give clear
indication of damage in all the cases even when
noise is incorporated in the simulated data. The
damage identification studies are carried out based
on the dynamic properties of the structures such as
natural frequency, mode shapes and their
derivatives using ANN and Genetic algorithm.

Jong Jae lee et.al [4] developed a neural networks-
based damage detection method using the modal
properties. This can effectively consider the
modelling errors in the baseline finite element
model from which the training patterns were
generated. In this method, the differences or the
ratios of the mode shape components between
before and after damage were used as the input to
the neural networks since they were found to be
less sensitive to the modelling errors than the mode
shapes themselves. Two numerical analysis on a
simple beam and a multi-girder bridge were
presented to demonstrate the effectiveness of the
proposed method. From laboratory tests on a bridge
model, it was found that the present neural
networks technique can be effectively used for
damage detection of the bridges under traffic
loadings considering the modelling errors. As a
result the damage locations were identified with
good accuracy for all the damage cases, whereas
the estimated damage severities contained minor
false alarms at several locations.

Dionysius M. Siringoringo and Yozo Fujino [5]
evaluated the system identification to a suspension
bridge using ambient vibration response. Two
output-only time-domain system identification
methods namely the Random Decrement Method
combined with the Ibrahim Time Domain (ITD)
method and the Natural Excitation Technique
(NExT) combined with the Eigen system
Realization Algorithm (ERA) were used. Accuracy and efficiency of both methods are investigated, and compared with the results from a Finite Element Model. The results of system identification demonstrate that using both methods, ambient vibration measurement can provide reliable information on dynamic characteristics of the bridge. Although both ITD and ERA methods were found to be reliable in identifying modal parameters, the performance of the NExT-ERA (Natural Excitation Technique – Eigen Realization Algorithm) technique was much better in regard to the efficiency in dealing with voluminous measurement data. The importance of this study is mainly on the application of efficient and reliable system identification in dealing with voluminous measurement data.

Shao – fei Jiang et al [6] presented a two-stage structural damage detection approach using fuzzy neural networks (FNNs) and data fusion techniques. Three FNN models were built, and then the crisp values of the FNN models were obtained and subsequently filtered by a threshold function. Consequently, a primary or rough assessment was made with FNN models (Fig.1a). Later, in the second stage, the crisp values output from three different FNN models in the first stage were input directly to the data fusion center where fusion computation was performed (Fig.1b). The final fusion decision was made by filtering the result with a threshold function. Hence a refined structural damage assessment of superior reliability was obtained. It was concluded that Fuzzy neural network and data fusion was superior to any individual technique, thus enjoys a promising prospect in structural damage detection.

Rama Mohan Rao [7] has discussed several computational techniques for structural health assessment. Several popular operational modal analyses both in time domain (e.g.: Ibrahim time domain, Eigen value realization algorithms, Least square complex exponential, stochastic subspace identification methods, random decrement etc.,) and frequency domain (peak picking, frequency domain decomposition and enhanced frequency domain decomposition etc.,) were discussed. Some very recent techniques like Hilbert Huang transformation, Blind source separation techniques have also shown great promise. These discussions provide rich information which SHM algorithms can utilize to detect, locate, and assess structural damage.

Kevin Tseng and Liangsheng Wang [8] presented the application of the electromechanical impedance method to detect the presence of damage and monitor its progression in concrete structures and was investigated using finite element analysis. The piezoelectric ceramic (PZT) patch bonded to concrete structures serves as both an actuator and a sensor in high frequency. The various health states of the structure were assessed using the root mean square deviation (RMSD) index. The harmonic response analysis in ANSYS was employed to investigate the correlation of the RMSD index with the location and extent of damage. A series of numerical studies conclude that there was a strong prospect in employing smart piezoelectric materials in estimating the location and extent of a damage.

Yan et.al [9] mainly dealt with the problem of damage detection using output-only vibration measurements under changing environmental conditions. Two types of features were extracted from the measurements, Eigen properties of the structure using an automated stochastic subspace identification procedure and peak indicators computed on the Fourier transform of modal filters. The effects of environment were treated using factor analysis and damage was detected using statistical process control with the multivariate Shewhart-\(T\) control charts. A numerical example of a bridge subject to environmental changes and damage was presented. The focus of this works was on the effect and the removal of the environment. In order to overcome the problems linked to the very large amount of data, the use of spatial filtering techniques was proposed.

Leandro Fleck Fadel Miguel et.al [10] developed a new approach for vibration-based procedures in an ambient vibration context. This method combines a time domain modal identification technique with the evolutionary harmony search
algorithm. A series of numerical examples with different damage scenarios and noise levels have been carried out in ambient vibration. Three cantilever beams with different damage scenarios were analyzed. The results showed that the proposed methodology has potential for the use of damage detection for the remaining life of the structure.

Soheil Saadat et.al [11] presents the application of a novel intelligent parameter varying (IPV) modeling and developed system identification technique to detect damage in base-excited structures. This IPV technique was compared with wavelet analysis method. These simulations confirm the effectiveness of the IPV technique, and show that performance was not compromised by the introduction of realistic structural non-linearities and ground excitation characteristics. This IPV technique overcomes the traditional model based and non-model based approaches.

Qindan Huang et.al [12] combined two techniques namely Bayesian model updating and vibration-based damage identification technique. To build a baseline finite element model, modal frequencies from the damaged structure were used. From the baseline model, mode shapes was used to detect the damage at local level. This approach involves the measurement and modelling errors in vibration tests and damage detection process respectively. The statistical uncertainties in the unknown modal parameters were also involved. As a result, modal data can be easily extracted from output only responses on an existing structure proving the proposed methodology to be practically valuable.

Srinivas et.al [13] carried out studies for the identification and localization of damage based on optimization techniques and modal-based approaches. The main drawback in this approach was the optimization procedure requires the evaluation of the objective function for the total population in each generation. Since it was computationally intensive a multi-stage approach has been proposed. At first, localization of the damage was achieved so as to reduce the number of parameters of the objective function in the optimization approach. These identified damaged elements were analyzed further for exact identification and quantification of the damage using genetic algorithm (GA) based optimization approach. The approach of using modal strain energy change ratio to identify damage at first-stage identification was found to be very useful in reducing the objective function parameters in the optimization method. This multi-stage approach was found to be very efficient in the exact identification and quantification of damage in structures.

Shiradhonkar and Manish Shrikhande [14] aimed at locating and detecting the damage in the beams with the aid of vibration based system identification and finite element model updating method. Usage of limited number of responses recorded during strong earthquakes is done in finite element model updating method. At unmonitored area the response of the structure whose degrees of freedom is estimated by interpolating recorded responses in time domain. Modal parameters are identified using empirical transfer function estimates and frequency domain decomposition. It is found that a combination of system identification techniques with sensitivity based finite element model updating can potentially locate and quantify the damage in a moment resistant frame.

3. CONCLUSION

A review of vibration based damage detection methodologies revealed numerous techniques and algorithms which utilized data in the time, frequency and modal domains. Structural damage detection is a complex problem, though many methods were developed, using structural vibration response and system dynamic parameter to detect damage, there are still a lot of difficulties in the practical application of these methods because of the complexity of structural damage and the uncertainty of various influencing factors. Research activities are still going on to find the most accurate and acceptable methods for the detection of damage parameters.

REFERENCES


