CHAPTER 2

LITERATURE REVIEW ON DAMAGE DETECTION AND HEALTH MONITORING

2.1 Introduction

Numerous investigations in the damage detection or health monitoring of structures have been vigorously carried out in the past decay. Some representative works, including theoretical developments, experimental validations, and practical applications, will be briefly reviewed in this chapter. Since the health monitoring approaches in this work are based on the modal parameters obtained from the structural vibrations, most reviews are focused on the modal-based (i.e. based on structural modal parameters) methods. Moreover, by the efforts of some researchers during these years, neural-network-based methods have become a major branch of studying structural health monitoring. Therefore, the health monitoring and damage detection related studies which were based on neural networks will also be reviewed herein.

2.2 Modal-Based Damage Detection And Health Monitoring

The modal-based methods utilize the information from modal parameters to detection and assess structural damage. The majority of this group of methods uses the lower modal frequencies and can best describe the global behavior of the structure. Therefore, they hold promise for global non-destructive inspection of a variety of structures, because surface measurements of a vibrating structure can provide information about the health of the internal members without costly dismantling of the structure. Also, because of their global nature, these techniques allow the customization of measurement points. Another major advantage is that the modal information is easy to extract from the measurements obtained through free, ambient, and forced vibration tests. A number of damage assessment techniques based on changes in structural modal parameters have been proposed. The concept underlying such an approach is that damage to a structure reduces its natural frequencies, increases the modal damping, and changes the modal shapes.

Various damage identification algorithms have been developed for dealing with three key problems, i.e., detection of the presence of damages, detection of the structural damage locations, and estimation of the damage extents. The first one problem is always involved in the second and third problems.

In early research, structural damage detection methods use natural frequencies as damage indicator. Salawu [14] made a comprehensive review on the detection of structural damage trough changes in frequency. However, from dynamic tests on bridges, Alampalli and Fu [15] and Salawu and Williams [16] concluded that the change in natural frequencies is not spatially specific and not sufficiently sensitive to detect local damage in the structure so that its application is limited. The results of their work indicate that the modal assurance criterion (MAC) and the coordinate modal assurance criterion (CMAC), which are based on mode shape data, are useful in detecting local structural change. Since mode shapes can provide much more information than natural frequencies, many studies have concentrated their efforts on damage detection with mode shapes information [17-19].

2.2.1 Methods for Detection of Structural Damage Location

For the damage localization problem, Cawley and Adams [20] proposed the first model by employing the changes in the natural frequencies, together with a finite element model (FEM), to locate the damage site of a given structure. Following their works, some researches [21, 22] have found this method susceptible to measurement errors, and ways of improving the localization have been introduced. Hearn and Testa [23] have illustrated that the ratio of the elemental strain energy to the total kinetic energy of the whole system is a fraction of the eigenvalue, and the ratio of this fraction for two different modes is dependent only on the location of the damage. Shi *et al.* [24, 25] presented a method based on modal strain energy for locating damage in a structure. Their method makes use of the change of modal strain energy in each structural element before and after the occurrence of damage. Some properties of the modal strain energy change are given to illustrate its sensitivity in locating damage.

By employing control-based eigenstructure assignment techniques, a subspace rotation algorithm was proposed by Zimmerman and Kaouk [26], in which the damage vector and relative rotation angle are used to identify the DOFs affected by damage. Lim and Kashangaki [27] put forward a similar method in concept using best-achievable eigenvectors, however, to identify the damaged structural members directly.

Yao *et al.* [28] presented a structural diagnosis technique using vibratory signature analysis and the concept of strain mode shape. When a structure experiences a damage or change, a new state of force equilibrium is realized. Since force distribution is, in general, greatest near the damaged area, the location of damage is implicitly identified by the severity of the strain mode shape change. Due to its sensitivity to local damage, strain mode shape change seems to be a suitable damage indicator for locating structural damage.

Stubbs and Kim [29] presented a methodology to localize and estimate the severity of damage in structures for which only postdamage modal parameters are available for a few vibratory modes. First, a theory of damage localization and severity estimation that utilizes only changes in mode shapes of the structures is outlined. Next, a system identification method that combines the experimental modal data and the modal parameters of a finite element model of the structure is developed to yield estimates of the baseline modal parameters for the structure. This method is attractive when the baseline modal information for the structure is unavailable.

Topole and Stubbs [30] used natural frequencies with mode shapes and showed the importance of introducing mode shape orthogonality to identify the location and extent of damage on a structure. Messina *et al.* [31] developed an assurance criterion for detecting single damage site of structures. And this method was extended to identify the relative amount of damage at multiple sites [22, 32]. Recently, Shi *et al.* [33] proposed a sensitivity-and statistical-based method to localize structural damage by direct use of incomplete mode shapes. This method is an extension of the work by Messina *et al.*[32]. The damage detection strategy is to localize the damage sites first by using incomplete measured mode shapes, and then to detect the damage site and extent again by using the more accurate measured natural frequency information.

Another important and interesting category uses the characteristics of the flexibility matrix. Unlike the stiffness matrix, the flexibility matrix can be formed more accurately through the usage of first several order experimental modal data. Lin [34] used this flexibility matrix to multiply the pre-damaged FEM stiffness matrix to determine the damage locations. Pandey and Biswas [35] used the change in flexibility matrix before and after the occurrence of damage in the structure as damage index to identify the location and amount of damage. An important advantage in this category is that the usage of the analytical model can be avoided. Also, some researchers used some special information such as curvature modes [36-39] and strain data [7] to search for the damage locations.

2.2.2 Methods for Estimation of Damage Extent

For the estimation of damage extent, one important class of methods for correlating measured modal data with analytical finite element models is the minimization or elimination of modal force error. This error is that resulting from the substitution of the analytical FEM and the measured modal data into the structural eigenproblem. Various approaches have been presented to minimize some measure of the error in the eigenproblem by perturbing the baseline values in the analytical model, such as the components of the stiffness, damping, and mass matrices. One type of method, known as sensitivity-based model update, uses the sensitivities of the modal response parameters of the FEM to the structural design parameters (such as Young's modulus, density, etc.) to iteratively minimize the modal force error [40, 41]. Another type of method, known as eigenstructure assignment, designs a controller that minimizes the modal force error [26, 27]. Further, another type of method, known as optimal matrix update, solves a closed-form equation for the matrix perturbations that minimize the modal force error or constrain the solution to satisfy it [42, 43].

Using modal parameters, Koh *et al*. [44] proposed an improved-condensation method to estimate the stiffness matrix that corresponds to observed degrees of freedom. Then, these authors detected local structural changes by quantifying changes in stiffness. Based on their own previous work [25], Shi et al. [45] further proposed an improved structural damage quantification algorithm. The algorithm includes the analytical stiffness and mass matrices of the system in the damage quantification. It reduces significantly the modal truncation error ad the FE modeling error from higher analytical modes in the computation.

2.3 Neural-Networks-Based Approaches

Over the last two decades, artificial neural networks have gradually been established as a powerful tool in the fields of prediction and estination, pattern recognition, and optimization [46-50]. Due to the features of robustness, fault tolerance, and powerful computing ability, the model of artificial neural networks becomes a promising tool in solving civil engineering problems, such as linear/nonlinear system identification, structural control and health monitoring.

2.3.1 Neural Networks for System Identification

There have been a lot of conventional identification methods for a linear dynamic system. For a nonlinear dynamic system, in contrast, few effective methods are available. A main difficulty in dealing with a nonlinear system lies in finding a reliable mathematical model for it. Neural network, however, does not rely on a preconceived mathematical model or even the number of parameters. The operation of neural networks in system identification for either a linear system or a nonlinear system is the same. Owing to its brilliant learning capability and its nonlinear nature, neural network is well suited for nonlinear system identification and was studied and applied to real-world problems [51]. Masri *et al.* [10, 52] has demonstrated in their studies that neural networks are a powerful tool for the identification of systems typically encountered in the structural dynamics field.

In the study of ANN-based system identification, Chen *et al.* [53] used ANNs to identify the structural dynamic system by using the structural responses recorded in a real apartment building during earthquake. The simulation results for a real multistory building subjected to earthquake ground motions had showed that the structural dynamic behavior can be well modeled by the trained neural networks. Based on the results the authors indicate great promise in structural dynamic model identification by using neural networks. The idea of this work was further applied to active control of structures [54]. Chassiakos and Masri [55] also explored the potential of using neural networks to identify the internal forces of typical systems encountered in the field of earthquake engineering and structural dynamics. After formulating the identification task as a neural network learning procedure, the method is applied to a representative chain-like system under deterministic and stochastic excitations. The neural network based identification method provides very good results for general classes of multi-degree-of-freedom structural systems.

Huang and Loh [56] proposed a network-based method for the modeling and identification of a discrete-time nonlinear hysteretic system during strong earthquake motion. They use two-dimensional models of a three-story frame and a real bridge in Taiwan subjected to several earthquake accelerograms to validate the feasibility and reliability of the method for estimating the changes in structural response under different earthquake events. It is shown that a multilayer neural network with nonlinear transfer function is a general type of NARMAX model, and is suitable for the extreme nonlinear input-output mapping problems.

Most ANN-based system identification models are non-parametric due to the feature of 'black box' in ANN model. Huang *et al.*, [13] developed a novel procedure for identifying the dynamic characteristics of structures. The dynamic characteristics are directly extracted from the weighting matrices of the neural network trained by observed structural responses and input base excitations. This work has firstly given a meaningful explanation on the black box form the view of system identification.

Other neural-based system identification related articles can be found in the references [57-59].

2.3.2 Neural Networks for Structural Health Monitoring

Recently, some researches have investigated the suitability and capabilities of ANNs for damage detection purposes. Ghaboussi *et al.* [59] and Wu *et al.* [60] discussed use of neural networks for detection of structural damage in a three-story frame with rigid floors. They trained neural networks to recognize the frequency response characteristics of undamaged and damaged structures. The varying damage levels were simulated by adjusting the properties of individual members. Elkordy *et al.*

[61] question the reliability of the traditional methods for structural damage diagnosis and monitoring that rely primarily on the visual inspection and simple on-site tests. They proposed a structural damage monitoring system for identifying the damage associated with changes in structural signatures using neural networks. For training, they used an FEM to develop failure patterns that were used to train a neural network so that it can later diagnose damage in the reference structure. Szewezyk and Hajela [62] presented a neural network approach based on mapping the static equilibrium requirement for a structure in a finite element formulation with the assumption that structural damage is reflected in terms of stiffness reduction. The results showed that even with input noise and incomplete measured data, neural networks can still obtain satisfying diagnosis.

Pandey and Barai [63, 64] trained a multilayer perceptron and a time-delay neural network respectively for the detection of steel-truss bridge structures. Zhao *et al.* [65] used a counter-propagation neural network to locate structural damage for a beam, a frame, and support movements of a beam. The required data such as natural frequencies, mode shapes and their other derivatives are obtained through the use of FEM.

The studies presented by Masri *et al.* [11], Nakamura *et al.* [12], and Masri *et al.* [66] used neural network-based approaches for the detection of changes in the characteristics of structure-unknown systems. Their approaches rely on the use of vibration measurements from a ‘healthy’ system to train a neural network for identification purposes. Subsequently, the trained network is fed comparable vibration measurements from the same structure under different episodes of response in order to monitor the health of the structure. Differ from other approaches, the attractive advantages of these approaches are that they do not require the analytical model for a real structure and only vibratory responses are used.

Zapico *et al.* [67] proposed a multi-layer-perceptron-based procedure for damage assessment in a two-storey steel frame and steel-concrete composite floors structure. A simplified finite element model is used to generate the training data. Sahin and Shenoi [68] presented a damage detection algorithm using a combination of global (changes in natural frequencies) and local (curvature mode shapes) vibration-based analysis data as input in ANNs for location and severity prediction of damage in beam-like structures. A FE model is used to introduce the damage scenarios to generate the training data. Other recent published works can be referred to the references [69-74].

All of the aforementioned investigations indicated that neural networks provide a powerful tool for linear/nonlinear system identification and structural health monitoring purposes.