CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

The civil infrastructure ages and deteriorates with time due to aging of materials, excessive use, overloading, climatic conditions, etc. All these factors contribute to the discard of constructed systems. As a result, health monitoring system which is capable of health monitoring (including damage diagnosis), issuing warning message, and providing maintenance guidance, become necessary to ensure the safety of the infrastructure and public. Health monitoring refers to the use of in-situ, nondestructive sensing, and analysis of system characteristics, including structural response, for the purpose of detecting system changes, which may indicate damage or degradation. Health monitoring techniques may be categorized into two groups, global and local health monitoring. Global approaches attempt to simultaneously assess the condition of the structure whereas local approaches employ non-destructive evaluation (NDE) tools on specific structural components.

Currently available NDE methods are mostly non-model methods, i.e., either visual or localized experimental methods, such as acoustic or ultrasonic methods, magnetic field methods, radiographs, eddy-current methods and thermal field methods. Accessing these techniques is time-consuming and costly. Some of them are also impractical in many cases such as in service aircraft testing, and space structure.

Almost all of these techniques require that the vicinity of the damage is known in advance and that the portion of the structure being inspected is readily accessible for human beings. Subject to these limitations, these non-model NDE methods can provide only local information and no indication of the structural strength at a system level.

Shortcomings of currently available NDE methods indicate a requirement of damage inspection techniques that can give global information on the structure and they do not require direct human accessibility of the structure. Furthermore, among with the continuous competing requirements of improving the weight, interdisciplinary performance, and reliability of structures, the development of effective, reliable, and real-time non-destructive health monitoring techniques based on the dynamic characteristics of the structures is receiving growing attention. Among them, the techniques of detect damage by monitoring changes in the dynamic characteristics or in the dynamic responses of the structure seem to be attractive and promising. To implement the on-line monitoring techniques, an essential condition is making the structure ‘smart’. This is the new generation of structures, often called ‘smart structure’.

A smart structure system has the ability to self-detect for potential damage, and the capacity to self-control and self-modify using sensors information (or observations) to achieve the demand system performance. Figure 1.1 illustrates the relationship between system performance, health monitoring, and damage diagnosis of a smart structure. A smart structure is generally considered to involve a network of sensors and actuators, real-time control capabilities, and health monitoring capabilities, to maintain the performance of the structure. The structure can inspect the health conditions of the structure automatically and continuously by itself. The actuator induces actuation into the structure, the sensors recognize and measure the structural responses, and the information from the sensors is acquired and analyzed by the control/processor unit.

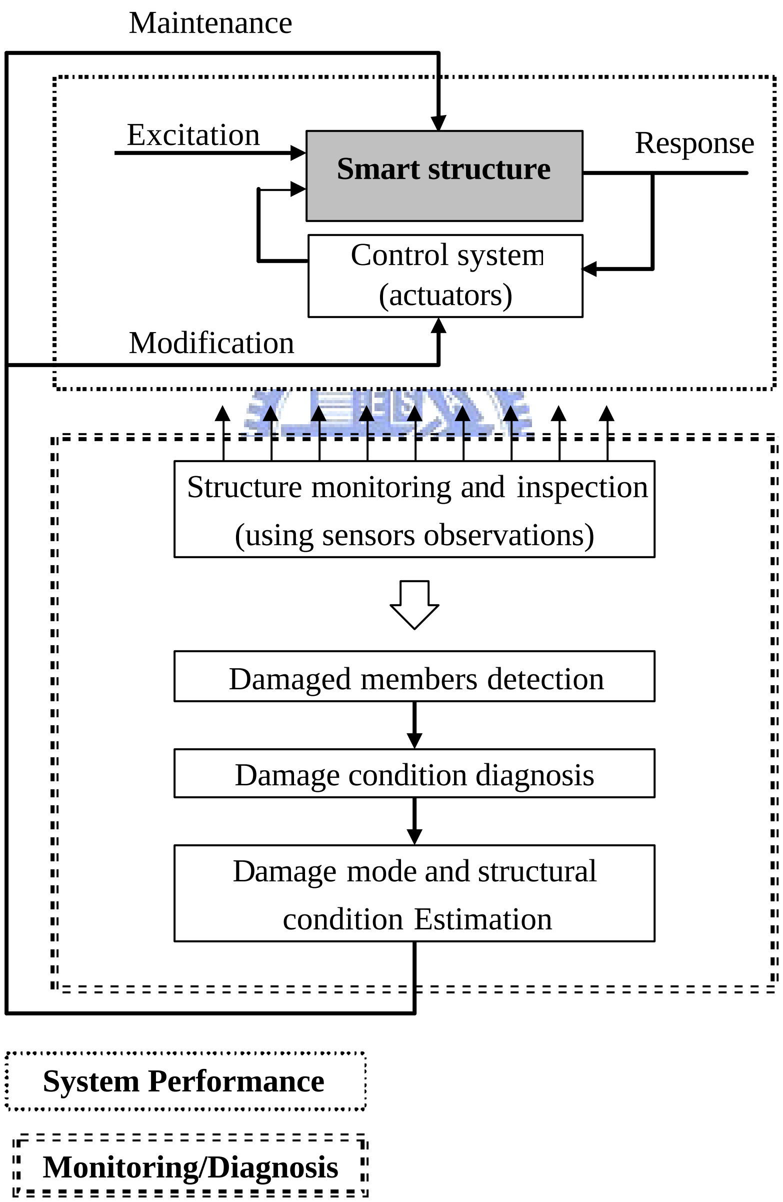

Figure 1.1 Illustration of the relationship between system performance and health monitoring (including damage diagnosis) of a smart structure

As a result of aging of materials, fatigue loading, corrosive environments, etc., critical structural systems continuously accumulate damage in their service environments. For such structures, periodic inspections and maintenance are necessary to ensure safety. An accurate and reliable damage detection capability for such structures is essential since damage that is not detected and not repaired may lead to disastrous structural failure.

Consequently, for the security and reliability during the service life, smart structures should have the potential to achieve the ultimate objective in damage detection, i.e., predicting the remaining useful life of the structure. The goals of developing smart structures in health monitoring is that the structure could, through the system identification process using vibratory observations, be able to detect damage as it is incurred by the structure, determine the location and extent of the damage, predict if and when disastrous failure of the structure will occur, and alert the operator as to how the performance of the structure is affected as that appropriate steps can be taken to remedy the situation. Therefore, system identification and damage assessment techniques are the foundations of developing the health monitoring system of smart structures. Figure 1.2 illustrates the relationship between system identification and damage assessment techniques.

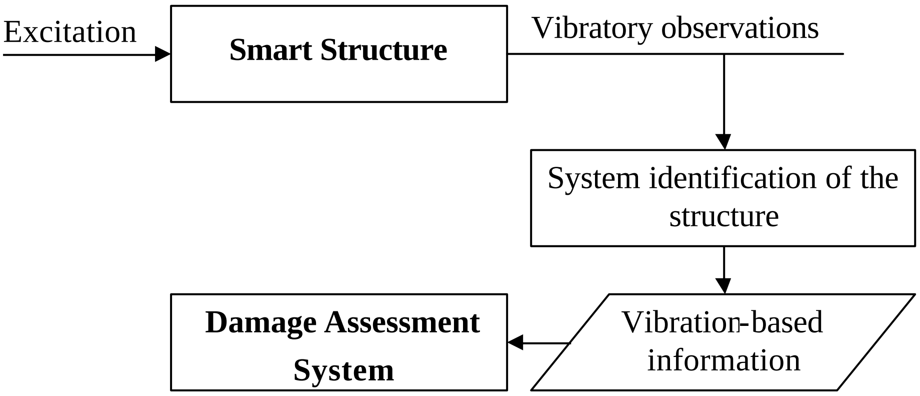

Figure 1.2 Relationship between system identification and damage assessment techniques.

1.2 Statement of the Problems

Recently, due to improved instrumentation and more understanding about the dynamics of the complex structures, the research of identifying the location and quantity of damage in structures has been received much more attention. Although encouraged applications have been conducted by some researchers during recent years [1-4], the damage assessment of complex civil engineering structures remains complicated and challenging [5].

A structure may sustain damage either when subjected to severe loading like a strong earthquake or when its material deteriorates. Traditionally, structural damage is assessed by visual inspection, which method is costly but inefficient. Visual inspection does find signs of damage such as cracks, spalls, and corrosion when these become visible; however, it is usually not possible when the signs of damage were inside the structure. Moreover, the relationship between such visible signs of damage and the corresponding condition or reliability of a structure is often very difficult to establish. There is lack of correlation between visual appearance and structural reliability for safety. In many cases, this leads to a great shortcoming in assessing the condition based on just visual inspections. During these years, various improved and innovative sensor (such as optical fiber sensors) technologies have been developed and applied to monitor buildings and infrastructures. It is desirable to analyze the measured data of a vibrating structure to determine whether a structure is damaged, the nature of any such damage and further, to assess the condition of the structure. Therefore, a significant amount of vibration-based damage detection methods have been conducted during the past decade.

The basic idea in vibration-based inspection is that modal parameters (such as modal frequencies and mode shapes) depend on the physical characteristics of the structure (such as structural mass, stiffness, and damping). Therefore, changes in the physical characteristics of a structure due to damage, such as reductions of stiffness, will lead to changes in its modal parameters. Based on this idea, numerous methods had been proposed in recent years. Some of the representative works will be briefly reviewed in Chapter 2.

The damage assessment of structures is an inverse problem. The solving procedure is basically implemented by looking for damage state (i.e. the location and extent of the damage in a structure) that exhibiting the observed phenomenon. Accordingly, damage identification can be regarded as a problem of pattern recognition. As known, the artificial neural networks (ANNs) had been proven suitable for pattern recognition; therefore, they are adopted in this work to solve the problem of structural damage detection. Furthermore, the possible damage state on the structure in most previous methods was determined by finding the damage state with the smallest discrepancy between the observed and analytical damage features (or patterns). However, the identification of damage state basing on certain observed damage features is an inverse problem; two similar but different damage states could possibly result in similar observations. As a result, the relationship from the observations to the damage state should be fuzzy but not crisp. Therefore, the fuzzy theory is also involved in the artificial neural networks and employed in this work.

Although there has been much development in damage detection of structures, as to practical applications, many difficulties should be overcome, such as the measurement uncertainties and inadequate test data, etc. Also, the most important difficulty stems from the difference between the analytical models and real structures. Generally, the error in analytical model may be classified into the following several aspects [6]:

(1). approximation in boundary conditions of analytical models may make the analytical stiffness matrix deviate from the practical one;

(2). connectivity conditions of elements in analytical models cannot reflect the real connective state of structural members;

(3). some important material parameters in analytical models, e.g. Young's modulus, may not represent the real ones;

(4). inherent variation in geometrical properties, e.g. length, width and thickness of structural members;

(5). there are many stiffness sources in practical structures, which are ignored in analytical models due to computational capacity; and

(6). the coarse mesh or unsuitable element types can cause the errors in analytical models.

Most of the approaches that had been developed employ the analytical models. For the practical applications, it may be more attractive to avoid employing too much information of the analytical models. If this can not be achieved, try making the proposed approaches more error tolerable and robust will be the alternative way. Due to the features of robustness, fault tolerance, and powerful computing ability, artificial neural networks seems to be a promising tool for solving this problem.

In addition to measurement uncertainties and errors, and discrepancy between analytical models and real structures, only part of structural DOFs can be measured in the vibration modes for practical applications is another difficulty in structural health monitoring. In the previous researches using analytical models, this difficulty is overcome by employing condensation techniques [7] or modal expansion techniques [8, 9].

Though the damage assessment of real structures remains difficult and challenging, it is expectable that if a spectrum of appropriate experiments and indices are integrated within a structural identification frame work, and the structure is monitored for a sufficiently long time, it is possible to accomplish successful condition and damage assessment.

1.3 Research Project

Modeling dynamic system by using neural networks has been increasingly recognized as one of the system identification paradigms. This work proposed artificial-neural-network-based approaches for the system identification (SI), system monitoring, and structural damage detection, respectively. The structural damage detection method is based the modal information of the intact and damaged structure. As the basis for structural damage detection, identification of the modal information is obtained through the proposed system identification models. The model, which is termed as ANN-based system identification (ANNSI) model, is based on a supervised artificial neural network and the concept behind the Ibrahim Time Domain (ITD) SI procedure for the identification of structural modal data. A properly arranged ANN, which is termed as modal analysis network (MAN for short), is trained by the recorded structural responses, the modal data (such as natural frequencies, damping, and displacement/strain mode shapes) can then be extracted directly from the connective weights. Since the physical properties can be obtained from the trained network, the network in this model is no more 'black box'. Furthermore, in the similar studies where the ANNs were employed for the system identification [10-13], the trained ANNs represent the dynamic characteristics of the structures. Hence, the trained network in ANNSI model not only can identify the structural modal data, but also can be used for system monitoring.

By using the modal data extracted from the structural responses via the aforementioned ANNSI model, the damage locations and extents in the structure are identified and evaluated. A two-stage damage assessment approach for building structures is proposed in this work. The first stage focuses on identifying the damage location in the damaged structure. As known, the identification of the damage location may be the most important but most difficult task in damage assessment of structures. This work proposed an ANN-based structural damage localization approach. This approach adopts an unsupervised neural network which incorporates with the fuzzy concept (named as Unsupervised Fuzzy Neural Network, UFN) for the purpose of damage localization. It is shown that the damage location is correlated with the changes in the modal parameters of the structure. Therefore, a feature of representing the damage location which terms as Damage Localization Feature (DLF) is obtained. When the structure experiences a damage or change in the structural members, the measured DLF is obtained through analyzing the recorded dynamical responses of the structure. Then the location of the structural damage can be identified using the UFN according to the measured DLF information. After the damage location was identified, the second stage works on estimation of the damage extent. Two simple algorithms are presented to estimate the damage extent. The first algorithm employs the changes of modal frequencies as well as modal shapes of the structure while the second one uses the changes of modal frequencies only.

The study in structural damage assessment and health monitoring has received more and more attention in recent year. There are not too much researchers in Taiwan, however, engaged in the experimental studies of structural damage assessment and health monitoring. Since the damage assessment of practical structures remains a difficult and challenging task, the author attempt to present a preliminary study on this topic as a reference. Consequently, a scaled-down four-story steel frame was designed to perform the experimental study in health monitoring of building structures. The conducted experiments aim to investigate the following topics: (1) verification of the proposed ANNSI model; (2) verification of the proposed damage diagnosis strategies; (3) investigation on the capabilities of the fiber Bragg grating sensors for structure monitoring; (4) exploration of other damage indicators related to structural damage; and (5) reference for the experiment investigation of damage diagnosis of large-scaled building structures.

A four-story steel frame, which is 2 m long, 2 m wide, and 6.4 m high, was built to perform the experiments. A series of shaking table tests of the experimental specimen was conducted in the laboratory in the department of civil engineering, National Chiao Tung University (NCTU). For the sake of structural responses measuring in the shaking table tests, three types of sensors, which are accelerometers, electrical resistance strain gages (RSGs), and optic fiber Bragg grating (FBG) sensors, were installed on the test model.

The structural deterioration is assumed in this work to be the change in story stiffness. In most experimental studies of damage assessment which is based on such an assumption commonly used bracing elements as simulations. According to the analysis result via ETABS software, however, even a small cross section of bracing can provide significant lateral stiffness which results in considerable change in natural frequencies of the structure. Therefore, not the bracing members but the ‘strengthening columns (SCs for short)’ are designed to provide the experimental specimen with additional lateral stiffness. Various deterioration classes, including the single-site deterioration class and the multiple-sites deterioration class are simulated in the experiments.

1.4 Objectives

The main purpose of this dissertation is to assemble a framework of the health monitoring system in a smart structure. In the health monitoring system, it is considered to involve three core parts which are the system monitoring, the system identification, and the damage assessment mechanisms. Figure 1.3 illustrates the relationship between these mechanisms.

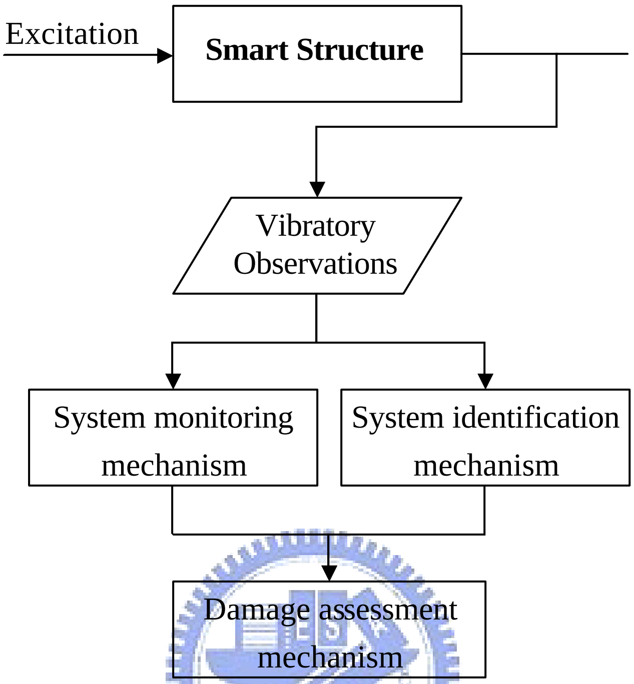

Figure 1.3 The frame of the health monitoring system.

To accomplish this goal, the author starts from the development of the ANN-based system identification models. These identification models can provide the information (such as the structural modal data) about the structure through the vibration measurements (such as the acceleration and strain responses) and can be used to continuously monitor the structure. Based on structural information provided by the identification models, the damage condition is assessed through the two-stage damage assessment approaches. At the first stage, a strategy based on structural modal data and an unsupervised fuzzy neural network for locating structural damage is developed. After the damage locations are identified, the damage extents are estimated at the second stage. In addition to the theoretical developments in system identification and damage assessment techniques, experimental study is also conducted to complete this work.

1.5 Dissertation Layout

In addition to introduction in Chapter 1, this dissertation is organized as follows.

In Chapter 2, a review related to the damage assessment and health monitoring studies is made. The approaches or methods that have been developed are appropriately classified and discussed.

Since artificial neural networks, in this work, play the main role in the system identification and damage assessment approaches, their basic theories and operations are briefly provided in Chapter 3. Two types of network model, a supervised back-propagation neural network with an L-BFGS learning algorithms and an unsupervised neural network with a fuzzy reasoning process, are adopted in this dissertation for different purposes.

In Chapters 4 and 5, the theoretical basis, used for system identification and damage assessment of structures in this dissertation, is presented. Chapter 4 shows the proposed ANN-based modal analysis model (named as ANNSI model) and system monitoring networks for parametric and nonparametric identification of dynamic systems, respectively. Since the ANNSI model and the system monitoring networks can identify the system change, they form the basis of damage detection and health monitoring approach of structures. Subsequently, Chapter 5 presents the ideas of damage assessment approaches for health monitoring purpose. Meanwhile, an example is presented right after each model and approach is introduced to examine the feasibility of the proposed methods.

In addition to the analytical study presented in Chapters 4 and 5, the dissertation also focuses on the experimental study of health monitoring in structures. For this purpose, dynamic experiments of a four-story steel frame were conducted on the shaking table (or seismic simulator) in National Chiao Tung University. Chapter 6 demonstrates the experimental setup for the shaking table tests on structural health monitoring study. In this chapter, the design of the experimental specimen, the measurement instrumentations, the idea and design of deterioration simulations, the simulated deterioration cases, and the experimental scheme are included.

After the experiments were implemented, the experimental measurements are applied to the system identification and damage assessment methods proposed in Chapters 4 and 5 for verification. The verification results will be shown in Chapter 7. The topics attempt to investigate will be also introduced in this chapter.

In Chapter 8, the framework for an integrated system, which is mainly constructed by the proposed methods of this work, for the health monitoring of smart structures is proposed. Some important issues that should be involved in the integrated system but are not investigated in this work are also briefly discussed herein.

In the end of this dissertation, certain conclusions on the analytical and experimental study are made, in Chapter 9, according to the results shown in the previous chapters. Furthermore, some suggestions for future study are also mentioned in this chapter as potential guidelines.