# CHAPTER 9

# CONCLUDING REMARKS

## 9.1 Summary

The main purpose of this work is attempted to assemble a framework of a health monitoring system for smart structures. The system is integrated with structural system identification methods, pattern recognition techniques (represented in neural networks), and structural monitoring/diagnosis methods. By investigating from analytical study to experimental study, the proposed framework for an ANN-based integrated system for structural monitoring and damage diagnosis is revealed adaptive and feasible.

According to the study results shown in this research, they are summarized and discussed in the succeeding sections.

### 9.1.1 Analytical Study

The analytical study, which is presented in Chapters 4 and 5, consisted of two parts:

(1) The first part is the development of ANN-based parametric and nonparametric system identification approaches. The nonparametric approach, which employs the global and decentralized monitoring networks,

can model the dynamic behaviors of the target structure or sub-structure, while the parametric approaches, which is termed ANNSI model, can generate the physical modal parameters of the structure.

(2) The second part is the development of ANN-based damage detection/diagnosis methods. The structural damage can be detected by the monitoring networks based on the prediction errors and by the UFN based on the measured modal parameters.

## ***Conclusions of the ANNSI Model***

A novel ANNSI model was proposed for identifying the modal parameters of a structure from its vibratory responses. The modal parameters are the fundamental basis for diagnosing a structure. The diagnosis is based on the fact that damage to a structure induces changes in the modal parameters of an equivalent linear system. Based on the theoretical development and example verification, some conclusions are made.

(1) The modal parameters can be directly estimated from the weighting matrices in the MAN of the ANNSI model by using either structural acceleration or strain measurements.

(2) The proposed model of estimating the modal parameters has been verified by excellent agreement between the present results and those results obtained by a subspace method, for an example of a five story steel frame under base excitation in a shaking table test.

(3) Continuous monitoring on the structural parameters provides reliable preliminary diagnosis on the structural integrity. This diagnosis procedure

has also been applied to the acceleration responses of the steel frame under various base excitations. The reported nonlinear responses to large earthquake input were found to change significantly modal shapes and damping values from those for the frame in small earthquake input.

(4) The damage detection approach that directly monitors the modal parameters changes is attractive from the view of without priori knowledge about the nature of a structure.

## ***Conclusions of the Monitoring Networks***

The monitoring approaches by using the monitoring networks rely on the use of vibration measurements from a 'healthy' system to train neural networks for identification purposes. Subsequently, the trained monitoring networks are fed comparable vibration measurements from the same structure under different episodes of response in order to monitor the health of the structure. It is found from the simulation results that:

(1) By investigated by the example of a five-story structure in shaking table tests, considerable prediction errors were found when the global monitoring network, trained with responses to the 20% Kobe earthquake input, was used to predict the responses to the 60% Kobe earthquake input. However, the prediction errors of the global monitoring network for the responses to the 10%, 40% and 52% Kobe earthquake inputs, from which no significant changes were found in the modal parameters, were much smaller than that for the 60% Kobe earthquake input responses. These results show the applicability of the monitoring network in diagnosing whether a structure is

healthy.

(2) It was shown in the numerical example of a six-story structure that, by monitoring the prediction errors from the decentralized monitoring networks, it is capable of identifying the damage location in story level by only using structural acceleration responses and input excitation.

(3) In the same way, the damage detection approaches that directly monitor the prediction errors from the monitoring networks are easy and attractive from the view of without priori information about the structure.

### ***Conclusions of the Damage Detection via UFN Model***

A novel approach, based on structural modal data and an UFN, is proposed in this work for the purpose of damage detection. After the damage feature is obtained based on the modal data of the structure, the damage site is located by matching two sets of the damage feature, ADLF and MDLF. The matching process is implemented using the UFN reasoning model. Numerical example of a five-storey shear-building structure was presented to extensively explore the feasibility of the proposed approach. Based on the simulation results showed in the example, some conclusions are made.

(1) The matching process based on the damage localization feature is a kind of pattern recognition which problem is suitable to be solved by using ANN. According to the verification results, the unsupervised neural network (such as UFN in this study) shows superior capability to the BPN when dealing with the problem of pattern recognition.

(2) Even with noise contaminated in the modal parameters, the UFN still has the

ability to identify the location of the damage with sufficient accuracy, while the BPN could possibly make incorrect diagnosis.

(3) The UFN performs well in damage localization when using truncated set of modal frequencies and incomplete mode shapes.

(4) The use of the fuzzy set in UFN made the detection more robust and flexible. The proposed approaches are very promising to be used for damage localization purposes.

### 9.1.2 Experimental Study

After the analytical study of the system identification and damage diagnosis was investigated, the proposed models and approaches were applied to the laboratory measurements, which were obtained from the experimental study of the structural monitoring and damage diagnosis, to further verify their capability and feasibility. According to the outcome of the experimental study, some discoveries are discussed and some conclusions are also made.

(1) The ANNSI model successfully identified the structural modal parameters of the specimen under various deterioration states from the measurements of the accelerometers, FBG sensors, and RSGs. The identified results show consistency between each of them.

(2) The induced deterioration can be reflected by the changes in structural modal parameters of the specimen. However, the modal parameters changes of the lower mode are not significant in the structure with slight deterioration.

(3) The FBG sensors do show their potentials in system identification and monitoring. The noise effect of the FBG sensors measurements is much smaller than that of the RSGs and accelerometers. This will make the identification easier when using the FBG sensors data. Furthermore, the distinguishing advantages of much less mass and great capacity of multiplexing a large number of sensors along a single fiber link make FBG sensors promising for health monitoring of practical structures.

(4) Compare with the CMS that based on the displacement mode shapes, the CSMS that based on the strain mode shapes is more sensitive to the structural damage. Moreover, the location of damage can be reflected by the sensing stations with larger value of CSMS. By using this approach, the damage location for the most simulated deterioration cases can be identified.

(5) The damage detection strategy that based on the prediction errors from the monitoring networks is easy to implement without limitation on the number of sensors. The increasing prediction error from the global monitoring network in the simulation of degradation development signifies deterioration of the structural integrity. Moreover, the larger prediction errors from the decentralized neural networks indicate the locality of the structural damage.

(6) Although the damage detection method that based on the DLF and the UFN model failed to be applied to the experimental measurements due to the problem of without a suitable analytical model, the damage diagnosis of the structure can still be carried out by other proposed strategies. If a suitable analytical model is available, the damage diagnosis of the structure will be improved and enhanced.

### 9.1.3 Integrated Structural Health Monitoring System

The integrated structural health monitoring system proposed in last chapter promises to be very feasible with the following supports.

(1) Since the methods and approaches involved in the system are mainly based on ANNs, the system is adaptive because ANNs are expected to improve their performance as they experience more episodes form the reality.

(2) The damage detection mechanism of the system was designed to integrate different diagnosis strategies to implement the similar tasks. In this way, even one of the diagnosis strategies fails to perform its duty, the system can still work properly.

(3) The system is independent of the methods used in each mechanism and is expandable. Any effective or improved method can be added to the corresponding mechanism to enhance the performance of the whole system.

## 9.2 Recommendations On Future Research

In this work, several ANN-based system identification models and damage detection strategies were proposed and demonstrated through extensive analytical and experimental study. These proposed models and approaches were designed to be integrated to organize a structural health monitoring system. Despite the encouraged achievements in this research, there are still many challenges and obstacles expected to be overcome and complemented in the future studies before a practicable and perfect system can be implemented in real infrastructures.

Following the unfinished works and the drawbacks of the proposed approaches, some potential directions on the future research are brought out.

(1) The ANNSI model was applied to the strain measurements to obtain the required structural strain model shapes. The relationship between the displacement modal data and strain modal data is preliminarily explored in this work. However, more conscientious and careful formulation on the theoretical basis of using strain measurements should be established.

(2) The damage diagnosis approach that based on the DLF and UFN presented in Chapter 5 requires an analytical model to generate the training patterns. Before obtaining a suitable analytical model, modification of the analytical model based on the real measurements is essential. The way of modification in this work is based on minimizing the difference between the measured modal frequencies and the analytical ones which method cannot generate an adequate analytical model for using. This problem may happen to all the model-based methods. Consequently, a more systematic and effective method for updating the analytical model should be studied.

(3) Due to the relative simplicity of the experimental specimen to practical infrastructure, the problem of deploying finite available sensors does not need to be considered in this work. However, it is indeed necessary to be considered for complex structures since the number of available sensors is always much lesser than the total DOFs of the structure.

(4) The method that involved in the warning mechanism of a health monitoring

system is not discussed in this work. As mentioned, the warning mechanism will produce proper strategic decisions which conventionally are made by experienced engineers and experts. To make the system automatic, an expert system is ideal to be included in the warning mechanism.

(5) In the experimental program, the test structure was excited in only one direction and the structure is assumed to vibrate as plane frame. Therefore, the torsion effect is assumed to be small enough to be considered and the measured signals are assumed to be uncoupled in multiple directions. However, these two problems should be noticed in the practical situations.

(6) The simulation of structural deterioration in this work is limited to story level, i.e. the deterioration is assumed to be reduction of story stiffness. Other types of damage simulations pointed out in front of Section 6.4, such as loss of mass, joint failure, and yielding failure, that could happen to a real structure are expected to be researched in the future.