Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

The research embodied in this dissertation reviews and extends the impedance-based structural health monitoring technique for detecting and identifying structural damage on various applications. Specifically, the research effort identifies the main limitations of the impedance method and extends the applicability of the technique. Furthermore the dissertation attempts to quantify structural damage by combining the impedance method with a model-based damage identification technique or neural network-based approach, and demonstrates the potential benefits of the integrated heath monitoring system. The analyses included in this research provide an extensive and valuable knowledge base that is of particular interest to the use of the impedance-based structural health monitoring technique for real-life field applications.

7.1 Conclusions

The main conclusions and contributions of this research effort can be summarized as follows:

- The effects of temperature changes on the impedance-based health monitoring technique have been investigated and a compensation method has been developed. Temperature changes result in a significant impedance variation, causing shifts of resonant frequencies and fluctuation of the magnitude, and hence, lead to an incorrect conclusion regarding the state of the structure. In order to minimize the effects of the temperature, an empirical based compensation technique, formulated by the reconstruction of damage metric, has been established. This technique has been applied successfully to a bolted pipe joint, a precision part (gear), and a composite reinforced structure, in the temperature range from 25-75 $°C$. It has been found that, by this compensation procedure, the impedance-based tehcnique extends its ability to detect incipient damage, even with the presence of significatnt temperature variation.

- Experimental investigations have been successfully carried out to detect damage on a quarter scale bridge section, where the bolts were progressively released. Our next example includes the implementation of the technique to detect real-time damage on a massive steel pipe header. It has been determined that the impedance-based technique is able to detect a very small size of hole (4x20 mm), which can be considered the mass loss of 0.002 % of an entire structure. The research also demonstrated that the impedance technique could determine damage under the adverse environment conditions, such as boundary condition changes, ambient loads, and impacts from an external source. It was seen that there are minor variations in the impedance signature, however, the values were substantially reduced by the compensation procedure. By the consistent repetition of tests, the capability and the robustness of this technology to monitor the conditions of various structures has been verified.

- The possibility of implementing the impedance-based health monitoring technique to monitor the structures under an extremely high temperature condition, well above 500 $^{\circ}C$, has been investigated. Through experimental investigations, the applicability of the impedance-based health monitoring technique to monitor such an extreme application was confirmed, with some practical issues to be resolved. The results from this research could provide an ample proof of the great potential of the impedance-based structural health monitoring technique to the extreme applications, where conventional NDE methods could not effectively approach the problem.

- The feasibility of using the impedance-based health monitoring technique for condition monitoring of civil critical facility has been investigated. The condition assessment can be made immediately, sine the time necessary to interrogate PZT patches and to interpret the measured impedance data is quick enough for on-line implementation. The capability of the technology has been demonstrated in monitoring the conditions of various civil critical facilities after a severe natural disaster as well as under normal operating conditions, when a quick assessment of a structure is urgently needed.

- A combined structural health monitoring technique has been established. In this methodology, two different damage detection schemes are integrated, including the impedance-based health monitoring technique and a wave propagation based modeling. A new wave propagation based technique to detect structural damage at high frequency range was developed for the quantitative assessment of structures. Measured frequency response function data, as opposed to modal data, were utilized to characterize the structural damage. The scenario is that PZT would be installed to monitor the structure using an impedance-base health monitoring technique, and if it gives a red light signal, more detailed inspection would be carried out to estimate the severity of damage, using this proposed technique. Numerical and experimental investigations on 1-dimensional structures were presented to illustrate the effectiveness of this technique.

- Artificial neural networks were integrated with the impedance-based structural health monitoring technique. Multiple sets of neural networks were developed in order to detect and characterize structural damage by examining changes in the measured impedance curves. A simulation beam model was investigated to verify the proposed method and experimental investigations were successfully performed to locate and identify the damage in a quarter-scale bridge section and in a space truss structure. This methodology integrates the advantages of the impedance method with the neural network features and can be applied to any complex structures, where no prior model is available and the use of FRF is unfeasible.

7.2 Recommendations

The research that is presented in this dissertation demonstrates the capability of the impedance-based structural health monitoring technique. Further research is required to address more challenging damage identification and structural health monitoring problems in the field.

The impedance analyzer (HP4194) used for experiments in this dissertation is still bulky and expensive equipment. The development of miniaturized and potable impedance measurement equipment is imperative for this method to be more easily applicable to real-field applications. As an alternative approach to the impedance-based health monitoring, the use of a self-sensing actuator (Dosch, *et al*. 1992; Pardo and Guemes 1998) for damage diagnostics is worthy of investigation, especially at high frequency ranges. The use of the self-sensing actuator may help solving one of the limitations of commercially available impedance analyzers, which the output voltage to excite the structure is limited to 1 V maximum.

The research performed in this dissertation is a first step in characterizing structural damage with use of the impedance-based health monitoring technique. The methods presented herein are combining the impedance method with the use of the model-based damage detection technique or the neural network-based approach, respectively. In order to lead to a final result in damage assessment more reliable and effective, it is recommended to integrate these three different approaches, the impedance method, model-based and neural network based damage identification technique, simultaneously. The issues related in this topic are not explored further in this dissertation, and are left for future work. Furthermore, there is one more interesting research area; to integrate the impedance-based technique with the existing well-known methods, such as ultrasonic, acoustic emission, or eddy current techniques. The combined approach would be very effective in the sense that most existing methods can provide details of damage in a structure, however require the knowledge of damage location in advance.

From the practical point of view, the long term reliability and durability of piezoelectric sensor-actuators, specifically the effects of aging, fatigue and depoling need to be further examined.

Some other practical issues of further research include:

- Packaging of the sensors to facilitate installation
- Possibility of wireless communication between sensor and signal processing equipment
- Issues related to the automation of the data acquisition process. The possibility of false alarms with the use of an automated software package and the inherent costs involves is also an issue that needs further investigation.
- Developing a methodology to assess the sensing area

Extensive efforts should be devoted to studying these implementation issues in order to handle real-life field applications.