Chapter 5

Conclusion and Future Work

5.1 Conclusion

A self-sensing and self-healing bolted joint has been developed. This concept encompasses the areas of health monitoring, joint dynamics and smart materials. Advancements in each of these areas were made to further the self-sensing and self-healing joint concept. The main conclusions and contributions of this research can be summarized as follows:

- A new method of making measurements for the impedance method has been developed and tested. A voltage divider circuit combined with an amplification circuit and FFT analyzer provides an accurate alternative to measure impedance for the health monitoring method that is of lower cost and volume.

- By making the impedance measurements substantially easier, miniaturized, and inexpensive, the impedance methods can now be readily applicable to the wide variety of real-life field applications. Furthermore, the outcome of this research points to a completely stand-alone, miniaturized impedance measuring device (without the use of FFT analyzer), by combining the device with a stamp-sized DSA or micro-controller and wireless communication technology.

- An experimental study has shown that impedance is a viable measure of torque. It is possible to use impedance to monitor changes in resonant peaks to quantify damage to joints.

- Approximate analyses were performed to test the plausibility of a model for joint friction. Both linear and approximate nonlinear finite element models for beam behavior were developed. The modal frequencies of the linear model matched the corresponding values for the monolithic system closely. The approximate nonlinear analysis was used to develop the relation between local linear damping factor and velocity amplitude. The analytical results matched the experimental results closely. This demonstrates the plausibility of the Bristle model and provides insight into changes in the width of peaks in impedance measurements.

- Modeling and experimental testing have shown that resistive heating of an SMA ring actuator in a bolted joint is possible. Shifts in the impedance functions of the structure from 25 ft-lbs to 10 ft-lbs then back toward the 25 ft-lbs shape indicate that joint tension was mostly restored in the resistive heating experiment.

- An exact value of the power required to completely heat the ring was not found, however, an upper bound of 240 W was found.

- Calculating the resistance of the ring using an equivalent diameter wire based on the cross sectional area of the wire was found to be accurate. The resistance, however, is very low, resulting in very large currents needed for heating. This necessitates the use of an uncommon power source, or high power device such as a car battery.

- The use of copper electrical leads sandwiched in the joint provide a simple means of electrical connection, without producing sparks.

- A more practical method of heating is to use an external heater using a conventional power source. The heating is slower so more attention needs to be paid to insulation.

- Alumina washers are effective at electrically isolating the system for resistive heating. However, they still allow a significant amount of heat loss from the ring when heating with an external heater so ceramic washers with a lower thermal conductivity are needed.

- With proper sizing and attachment the power required to heat the SMA washer with an external heater is less than 45 W.

- A method of sizing SMA ring actuators based on a technique provided by Intrinsic Devices, Inc. has also been shown. A simple model predicts the force developed by various sizes of actuators in the bolted joint configuration.

- The concept of the self-healing bolted joint has been presented at the Stanford Structural Health Monitoring Conference. The investigation of damping was presented at the International Modal Analysis Conference (IMAC). The low-cost impedance method has been presented at the Stanford conference and IMAC as well as SPIE's Symposium on NDE for Health Monitoring and Diagnostics and the US National Congress of Theoretical and Applied Mechanics. A paper presenting the low-cost impedance method has been submitted to the Journal for Intelligent Materials Systems and Structures.

5.2 Future Work

The research that is presented in this thesis demonstrates the capability of the self-sensing and self-healing joint concept incorporating the impedance-based structural health monitoring technique and a SMA washer. Further research is required to address more challenging damage identification and structural health monitoring problems in the field. The impedance method integrated with other techniques such as neural networks or fuzzy systems should be applied to quantitatively detect the loss of preload in joints.

Several issues that bear investigation regarding the low cost impedance method include the effect of varying the driving voltage due to different sensing resistances, the development of miniaturized impedance measuring device without the use of a separate FFT analyzer and the combination of the impedance method with wireless communication technology.

More research should also be conducted concerning the implementation of the SMA washer for restoring bolt preload. A complete model including the mechanics of the bolt, additional members of the joint and SMA washer and SMA transformation when heated should be developed to address sizing of SMA washers and perhaps be used in controlled heating. Such a system could utilize the pulse width modulation heating method where current pulses of uniform magnitude are varied in duration to control the energy input. In order for this to develop the control system would also need the tension in the bolt from an accurate quantitative health monitoring method. Improvements in the insulating ability of the ceramic washers, durability of the washers, sizing of the heating elements when using an eternal heater and attachment of the heating element should be investigated.

These issues should be addressed before implementation in real-life field applications.