

## Chapter 6

### Conclusions

#### 6.1 Summary

A special test rig was used to evaluate the effectiveness of actively controlled PZTs for reducing vibrations in the test structure. The test rig consisted of a test plate that was clamped rigidly around its edges and was excited by an electromagnetic shaker. The data for the shunted and active PZT tests was recorded on a Hewlett Packard dynamic signal analyzer with accelerometers attached to the excitation frame and the test plate.

In the active PZT tests, the controller was implemented through a dSPACE board with Matlab's Simulink toolbox. The particular control law used for the active PZT tests was positive position feedback, which used a generalized displacement measurement for the feedback control. There were several different active control systems designed for vibration suppression of the test plate. Initially, experiments were performed to implement a self-sensing PPF technique where the PZT was used as the sensor and actuator for the control system. This controller, however, was difficult to implement and had stability problems. To solve this problem, a modal domain optical fiber sensor was implemented to replace the self-sensing PZT. This controller was much easier to implement and was more robust than the self-sensing technique. The controller, as explained in Chapter 4, used from one to six PPF filters, in parallel, to accomplish the control.

The active control technique that was developed for testing was also able to simultaneously detect damage on the test plate, such as a loose bolt in the clamping frame. This damage detection technique used the PZT to get an impedance measurement of the test plate. The impedance curve of the structure was measured on a Hewlett Packard Impedance Analyzer by exciting the test plate from 45 to 55 KHz with the PZT.

The results of the active PZT tests show that this high frequency excitation does not affect the stability or performance of the control system. In addition, Chapter 4 described how the active control technique was able to successfully control vibration levels as the temperature of the test plate was increased from 25 °C to almost 50 °C. These additional features make the particular active PZT technique used in this study more of a multi-purpose controller than the shunted PZT technique.

The data taken with the Hewlett Packard dynamic signal analyzer shows that smart materials can significantly reduce the vibration levels in the test plates. The test results show that the shunted PZT technique can reduce vibration levels by up to 22 dB and 14 dB in the undamped and unshunted test plates, respectively. In addition, broadband frequency reductions of 11 dB were achieved between the undamped and shunted test plates. The test results with actively controlled PZTs show a reduction in vibration levels by up to 19 dB and 23 dB in the undamped and uncontrolled test plates, respectively. A broadband analysis of the active PZT test results showed reductions of 16.5 dB and 14 dB in the undamped and uncontrolled test plates, respectively.

The comparison between the shunted and active PZT damping techniques used in this study shows that active control with positive position feedback was more effective at controlling the vibration levels of the test plate. The active PZT method was able to add damping to each of the modes targeted in the frequency range of interest. In addition, active control with positive position feedback was able to achieve this level of control authority with a single PZT patch located in the center of the test plate. Conversely, the shunted PZT technique used three PZT actuators to reduce the vibration levels of the test plate. In Chapter 5, metrics were developed to quantify the amount of dB reduction per area of PZT actuator. These metrics showed that the active PZT method was able to achieve a significantly higher dB reduction per area of PZT actuator – over four times that obtained with the shunted PZT technique. Next, a discussion of future research in the area of smart material systems is provided.

## 6.2 Recommendations for Future Research

The results of the active PZT tests showed strong potential for further research in the area of simultaneous active control and health monitoring of structures. The particular controller used in this study can be used in many applications, ranging from sports equipment to automotive and aerospace applications. Basically anywhere that structural vibration suppression and damage detection are important. However, the applications of smart materials and the ultimate benefits of the research presented in this paper can only be determined by applying smart material technologies to actual structures.

The research conducted for this paper has shown potential for further research in many areas of smart material technologies. One area in particular that needs further investigation is the placement of PZTs on structures. A finite element analysis was used to determine areas of high strain energy and actuator placement for this study. However, in practical applications it is more difficult to determine areas of high strain energy for structures more complicated than a plate. A finite element method could prove useful in determining PZT placement and also predicting structural damping with PZTs. Another area that could use further investigation is the amount of PZT actuator required to control a structure. This research could improve the effectiveness of controllers and reduce the overall added structural weight.

In Chapter 5 of this paper, a comparison was made between the RLC shunt technique and the active PZT technique. This study compares only one type of shunt circuit with one feedback control law. Therefore, future work could include comparisons between the different types of shunt circuits and active control laws. This investigation would help evaluate the effectiveness of alternative shunting and active control techniques, and help classify these techniques for different structural applications.

There is still a considerable amount of work that can be done in the area of digital PPF. To date, the author has found very little information on this subject in relation to its potential for control. The work in this area could include a comprehensive stability analysis in the continuous and digital domains, a study of the required number of PPF filters, and a study of the tuning process of each filter. The tuning process for this research consisted mostly of a trial and error procedure for each filter of the controller.

The design of multi-purpose digital PPF controllers is perhaps the area with the most potential. The controller designed in this study was able to control the vibrations of the test plate and detect damage in the face of temperature changes. This simultaneous active control and health monitoring system was able to control the structural vibrations as the temperature of the structure was increase from 25 °C to almost 50 °C. However, the parameters of the controller were manually adjusted to account for the effects of these temperature changes. Future work in this area could include designing an adaptive controller that identifies these structural changes and adjusts the system's parameters accordingly. In the area of damage detection, future research could focus on identifying the specific type of damage that has occurred. In the research conducted for this study, the damage detection system was only able to identify that damage has occurred, not the particular type of damage.