# Passive and Semi-active Vibration Control of Piezoelectric Laminates

A thesis presented
by

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# Declaration

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

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# Acknowledgments

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I wish to extend my appreciation to Dr. Will Heath who attempted to answer all theoretical questions. The author wishes to acknowledge the help of Mr. Andrew Fleming and Mr. Matthew Smith for their assistance in this work. Also, Mr. Tim Wylie and Mr. Russel Hicks are acknowledged for their practical ideas.

On a personal note, I would like to thank my parents who offered their love and support in time of need. Also, my good friends Andrew, Marco, Scott and Eggy.

# Contributions

Some of the work presented in this thesis was in collaboration with Dr. S. O. Reza Moheimani and Mr. Andrew Fleming. Dr. S. O. Reza Moheimani introduced the concept of optimal shunting damping. Design, construction and testing of the synthetic impedance circuit were in collaboration with Mr. Andrew Fleming. The negative capacitance (semi-active) controller was also in collaboration with Mr. Andrew Fleming. All other theoretical work and implementation presented was solely mine.

The simply supported beam experimental apparatus was designed by myself. Mr. Russel Hicks constructed the experimental apparatus; this work included gluing the piezoelectric laminate patches onto the beam structure and the construction of the bench clamps.

This project was considerably aided with the financial assistance of the Center of Integrated Dynamics and Control (CIDAC), Australian Research Council (ARC), University of Newcastle Postgraduate Research Scholarship (UNRS) and the Department of Electrical & Computer Engineering, University of Newcastle, Australia.

# Publications

During the course of this research, a number of papers have been submitted to international journals and conferences. The following is a list of those articles, which have already appeared in an international journal or have been submitted for publication. Conference papers, which have been presented or submitted for presentation, are also listed. Technical reports and patents follow these international publications.

- **Journal Publications**

1. A. J. Fleming, S. Behrens and S. O. R. Moheimani. Synthetic impedance for implementation of piezoelectric shunt damping circuits, **36**(18):1525-6, *IEE Electronics Letters*, 31st August 2000.

2. A. J. Fleming, S. Behrens and S. O. R. Moheimani. Optimization and implementation of multi-mode piezoelectric shunt damping systems. Submitted to *IEEE/ASME Transactions on Mechatronics*, 2000.

3. S. Behrens, A. J. Fleming and S. O. R. Moheimani. Negative capacitor for multiple mode semi-active shunt damping of a piezoelectric laminate beam. Submitted to *IEE Electronics Letters*.

- **Conference Proceedings**

1. A. J. Fleming, S. Behrens and S. O. R. Moheimani. A new approach to piezoelectric shunt damping. *In: Proceedings of International Symposium on Smart Structures and Microsystems*, Hong Kong, October 2000.

2. A. J. Fleming, S. Behrens and S. O. R. Moheimani. Innovations in Piezoelectric Shunt Damping. *In: Proceedings of SPIE: Smart Structures and Devices 2000*, Melbourne Australia, 13-15th December 2000.

3. S. Behrens and S. O. R. Moheimani. Optimal resistive elements for multiple shunt damping of a piezoelectric laminate beam. *In: Proceedings of IEEE Conference on Decision and Control*, Sydney, Australia, December 2000.

- **Technical Reports**

1. A. J. Fleming, S. Behrens and S. O. R. Moheimani. Synthetic impedance for damping of smart structures. Technical Report EE0016. The Department of Electrical and Computer Engineering, University of Newcastle. March 2000.

2. S. Behrens and S. O. R. Moheimani. Optimal resistive elements for multiple mode shunt damping of a piezoelectric laminate beam. Technical Report EE0015. The Department of Electrical and Computer Engineering, University of Newcastle. March 2000.

3. S. Behrens and A. J. Fleming. Negative capacitor for multiple mode semi-active shunt damping of a piezoelectric laminate beam. Technical Report EE0045. The Department of Electrical and Computer Engineering, University of Newcastle. October 2000.

- **Patents**

An impedance synthesising arrangement, an improved vibrational damping apparatus and a method for deriving a digital signal processing algorithm. (Lodged: May 2000 - Pending)

# Abstract

This thesis considers a number of related problems in the areas of passive and semi-active vibration control of piezoelectric laminates.

The thesis consists of three main parts. The first part of the thesis develops a mathematical model of a physical resonant system–piezoelectric laminated simply supported beam. It is essential to have a good understanding of the physical system so that the associated problems with passive and semi-active shunt damping can be addressed.

The second part of the thesis is concerned with problems related with current passive shunt damping techniques using a single piezoelectric laminate. One of the current problems with multiple mode techniques is determining the correct resistive damping for each resonant mode. Therefore, a systematic method is presented for determining the optimal resistance elements by minimizing the $\mathcal{H}_2$ norm of the damped system. After the design process, shunt circuits are normally implemented using discrete resistors, capacitors and virtual inductors (Riordan Gyrators). The difficulty in constructing the shunt circuits and achieving reasonable performance has been an ongoing problem. A new approach to implementing piezoelectric shunt circuits is presented. A "synthetic impedance", consisting of a voltage controlled current source and digital signal processor (DSP) system, is used to synthesize the terminal impedance of a required shunt network.

The third part of the thesis is concerned with is semi-active vibration control of piezoelectric laminates. This part addresses a number of associated problems with the current passive shunt damping schemes. The foremost being the complexity of the shunt circuits required to dampen multiple modes. They generally act to minimize structural vibration at a specific frequency - which are rarely stationary. Therefore, a new broadband semi-active shunt technique for controlling multiple modes has been developed. The "negative capacitor" controller is proposed theoretically, and then validated experimentally. The negative capacitor is similar in nature to a passive shunt damper as it uses a single piezoelectric transducer to dampen multiple modes of a flexible structure.

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