CHAPTER 5. SUMMARY AND CONCLUSIONS

5.1 SUMMARY OF NUMERICAL ANALYSIS

The application of piezoceramic stack actuators as actuators for active vibration control has been examined for three types of physical structure; beams, plates and cylinders. For each type of structure, a theoretical model has been developed to describe the vibration response of the structure to excitation by point forces and to active vibration control using piezoceramic stack control actuators and vibration sensors. The effect of stiffeners on the vibration response of the structures has been included where appropriate.

The analysis of vibration in a beam was a one dimensional problem. An analytical model was developed from the one dimensional equation of motion for beams to describe the vibration response of an arbitrarily terminated beam to a range of excitation types. The numerical results indicated that flexural vibrations in beams can be effectively controlled using a single piezoceramic stack actuator and angle stiffener control source and a single vibration error sensor.

The dependence of the control force amplitude and phase and the attenuation of vibration level achieved on a number of parameters was investigated. It was found that the magnitude of the control force required for optimal control generally decreased with increasing stiffener flange length and increasing frequency. The control force amplitude required for optimal control was less when the beam was excited at a resonance frequency.

When there was reflection from the beam terminations, the optimum control force was either in phase or 180^o out of phase with the primary source, but when there was no reflection from beam terminations (the infinite beam case), the control force phase cycled through 180^o as the excitation frequency was increased.

Comparison between the results obtained for infinite beam and finite beam cases indicated that the standing wave generated when there were reflections from beam terminations had a significant effect on the effectiveness of active vibration control. Maxima occurred in the control force amplitude required for optimal control when the separation between control and primary sources was given by $x = (c + n\lambda_b/2)$ where n is an integer and c is a constant dependent on frequency and the type of boundary condition. These maxima occurred when the control source was located at a node in the standing wave generated by reflection from the beam terminations. Minima in the mean attenuation of acceleration level downstream of the error sensor also occurred when the control source was located at a node in the standing wave.

When the error sensor was located at a node in the standing wave in a finite beam, the attenuation achieved was less than that achieved with the error sensor located away from a node. However, locating the error sensor at a node did not affect the control force amplitude required for optimal control.

Increasing the separation between the primary and control source did not improve the attenuation. The amount of attenuation achieved downstream of the error sensor increased with increasing separation between the error sensor and the control source.

Numerical results also indicated that it is possible to achieve reductions in acceleration level upstream of the primary source as well as the desired reduction downstream of the error sensor. The maximum mean attenuation in acceleration level upstream of the primary source was theoretically achieved with the separation between primary and effective control source locations given by $x = (c + n\lambda_b/2)$ for $n = 1,2,3...$ For error sensor locations outside the control source near field, the mean attenuation of acceleration level upstream of the primary source did not depend on error sensor location.

An analytical model was developed from the two dimensional equation of motion for plates to describe the vibration response of a plate to a range of excitation types. Two sets of boundary conditions were considered, both with simply supported sides. One plate was modelled as free at both ends, and the second was modelled as semi-infinite in length. The effects of the mass and stiffness of an across-plate stiffener were included in the analysis. The numerical results indicated that flexural vibrations in stiffened plates can be effectively controlled using the piezoceramic stack actuators and a line of vibration error sensors.

The numerical model showed that control of plate vibration is a similar problem to control of vibration in beams, but the added width dimension necessitated more than one control source and error sensor across the plate width to achieve optimum control.

Like the corresponding beam case, the mean amplitude of the control forces required for optimal control of plate vibration generally decreased with increasing frequency. The optimum control forces were either in phase or 180^o out of phase with the primary sources. This was true for the semi-infinite plate as well as the finite plate, because a standing wave was generated by the vibration reflections from the finite end and the angle stiffener. This was not so for the infinite beam case, as the beam was modelled as infinite in both directions and the mass loading of the angle stiffener was neglected.

Maxima occurred in the mean control force amplitude required for optimal control when the separation between control and primary forces was given by $x = (c + nx_s)$ where n is an integer, c is a constant dependent on frequency and the type of boundary condition, and x_s is the separation between axial nodes in a standing wave. These maxima occurred when the control sources were located at a nodal line in the standing wave generated by reflection from the plate termination and the angle stiffener. Minima in the mean attenuation of acceleration level downstream of the error sensor occur when the control sources were located at a nodal line in the standing wave. Increasing the separation between the primary and control sources did not improve attenuation provided the control sources were located outside of the primary source near field.

The amount of attenuation achieved downstream of the error sensors increased with increasing separation between the error sensors and the control sources. When the line of error sensors was located at a nodal line in the standing wave that exists in finite plates, the attenuation achieved was less than that achieved with the error sensors located away from a node. Locating the error sensors at a node did not affect the amplitude of the control forces required for optimal control.

As more than one control source was used in the plate model, consideration was given to the effectiveness of active vibration control with the control sources driven by a common signal and with the control sources driven independently. At low frequencies, there was very little difference in the mean control effort required for optimal control and the mean attenuation downstream of the line of error sensors achieved, between control using independent control sources and control sources driven by a common signal. At higher frequencies when higher order across-plate modes became significant, very little attenuation was achieved with control sources driven by a common signal. Good reduction in acceleration level was achieved with independently driven control sources right across the frequency range considered. It was determined that use of three independently driven control sources and three error sensors was sufficient to give optimal attenuation.

Both the beam model and the plate model were extended to include a second angle stiffener and control source(s) downstream from the first, with the aim of controlling the vibration better when the first control source was located at a node in a standing wave. The magnitude of the first control force(s) was limited to a maximum value, and the second control source(s) used when the limit was reached. The maxima in control force amplitude and the minima in attenuation that occurred when the first stiffener and control source(s) were located at a standing wave node were eliminated in this way.

It was shown, for the beam case, that there was no simple practical method of using a second error sensor to eliminate the minima in attenuation that occur when the first error sensor is located at a standing wave node, because of the difficulty in determining when the first error sensor was located at a node without the introduction of several more error sensors.

The analysis of vibration in a cylinder was a significantly more complicated problem than the beam and plate cases. The Flügge equations for the vibration of a cylinder in the radial, axial and tangential directions were used to develop a model to describe the vibration response of a ring-stiffened cylinder to a range of excitation types, and in particular to point force primary excitation sources and angle stiffener and piezoceramic stack control sources. The numerical results indicated that flexural vibrations in cylinders can be actively controlled using piezoceramic stack actuators placed between the flange of an angle stiffener and the cylinder surface.

The cylinder vibration response was different to the simpler cases of the plate and beam in two main ways. In the cylinder, vibration in the axial, tangential and radial directions was significant, and the separation x_s between axial nodes in standing waves was much longer than that in the plate and beam cases considered.

Vibration amplitudes in the radial, axial and tangential directions were of similar order.

Modes of axial and radial vibration occurred at the same tangential locations while modes of tangential vibration were located out-of-phase relative to the axial and radial modes. Optimally controlling radial vibration also significantly reduced axial and tangential vibration levels.

Because the separation x_s between axial standing wave nodes in the cylinder was so large, the mean amplitude of the control forces required for optimal control did not greatly dependent on frequency, axial control source location or axial error sensor location. There were minor fluctuations, particularly for the finite cylinder, but no pattern or increasing or decreasing trends. There were no axial locations of control sources and error sensors that gave maxima in control force amplitude or minima in attenuation.

Like both the plate cases and all but the infinite beam cases, the optimum control forces were either in phase or 180^{o} out of phase with the primary sources. This was true for the semi-infinite cylinder as well as the finite cylinder, because a standing wave was generated by the vibration reflections from the finite end and the angle stiffener.

Increasing the separation between the primary and control sources did not greatly affect the attenuation achieved downstream of the ring of error sensors. Increasing the separation between the error sensors and the control sources improved the mean attenuation of acceleration level downstream of the ring of error sensors.

Little or no reduction was achieved with control sources driven by a common control signal, because higher order circumferential modes of vibration contribute significantly to the vibration response of the cylinder even at low frequencies.

The circumferential location of the control sources was significant. Generally, for every control source, there were two locations at which placement of an additional control source required excessive control force amplitudes for optimal control. Four control sources and four error sensors were sufficient to achieve optimal attenuation of cylinder vibration.

5.2 SUMMARY OF EXPERIMENTAL RESULTS

For at least one example of each of the three structure types considered, the theoretical model outlined was tested experimentally. In each experiment, the acceleration distribution resulting from measured force inputs was gauged and compared with the theoretical predictions, both with and without active vibration control.

Experiments were performed on a beam with four different sets of end conditions. The impedance corresponding to each termination was first calculated from experimental data. Comparison between experimental results and theoretical predictions showed that the accuracy of the theoretical model when compared to the experimental results was very high, both in predicting the control force amplitude and phase required relative to the primary force, and in determining the acceleration distribution occurring along the beam. The impedances calculated from experimental measurements gave more accurate results than the "classical" impedances corresponding to each termination. The theoretical model accurately predicted the amount of attenuation that could be achieved experimentally.

The theoretical model outlined for the plate was verified experimentally for a plate with simply supported sides, one end free and the other end anechoically terminated. A modal analysis of the plate indicated that the anechoic termination allowed some reflection and so did not exactly model the ideal infinite end, and that the angle stiffener made a significant difference to the vibration response of the plate. Comparison between experimental results and theoretical predictions for the vibration of the plate with and without active vibration control showed that the theoretical model accurately predicted the vibration response of the plate for the uncontrolled case and the case with control sources driven by the same signal. The angle stiffener reflected more of the vibration and transmitted less than the theoretical model predicted. The theoretical model predicted more attenuation than could be achieved experimentally for the case with independently driven control sources. An error analysis indicated that an error in the control source signal of 0.1% would have produced a decrease in attenuation corresponding to the difference between the theoretical prediction and the experimental result. Nevertheless, around 25 dB attenuation was achieved experimentally for the case with independently driven control sources.

Experiments were performed on a cylinder with simply supported ends. A modal analysis of the cylinder indicated that the angle stiffener made a significant difference to the vibration response of the cylinder and that higher order circumferential modes contributed significantly to the overall cylinder vibration response. Comparison between experimental results and theoretical predictions for the vibration of the cylinder with and without active vibration control showed that the theoretical model accurately predicted the vibration response of the cylinder for the uncontrolled case and the case with control sources driven by the same signal. The theoretical model predicted more attenuation than could be achieved experimentally for the case with independently driven control sources. Again, an error analysis indicated that an error in the control source signal of 0.1% would have produced a decrease in attenuation corresponding to the difference between the theoretical prediction and the experimental result. Around 18 dB attenuation was achieved experimentally for the case with independently driven control sources. Finally, experimental measurements indicated that the amplitudes of axial and tangential vibration were of similar order to the radial vibration amplitude, as predicted by the theoretical model, for both uncontrolled and controlled cases.

5.3 Conclusions

It is possible to actively control vibration in stiffened structures using actuators placed between a stiffener flange and the structure surface. Actuators placed across the width of a plate-like structure or around the circumference of a cylindrical structure at a single axial location can be used in conjunction with a line or ring of error sensors to significantly reduce the vibration transmission along the structure.

The theoretical models outlined in this thesis can be used to determine the maximum amount of vibration reduction that can be achieved under ideal conditions. It may not be possible to achieve the predicted level of reduction in practice, but high levels of attenuation are achievable.

When the separation between nodes in the axial standing wave in the structure is less than the length of the structure, for any given frequency of excitation, there will be discrete axial locations of control sources that will not yield high levels of attenuation, or, for given locations of control sources, there will be certain frequencies at which vibration cannot be controlled effectively. This occurs when the control source location or error sensor location corresponds to a node in a standing wave generated by reflections from the structure terminations and stiffeners. It is possible to overcome this difficulty simply with a second set of control sources at another axial location. The level of attenuation is also reduced, but not as much, when the error sensor location corresponds to a standing wave node. Introduction of a second set of error sensors does not yield a simple solution to this problem.

The separation between nodes in the axial standing wave in typical cylindrical structures is very long, so axial location of control sources and error sensors is not critical.

Increasing the separation between the error sensors and the control sources increases the maximum reduction in acceleration level that can be achieved in each type of structure considered. Increasing the separation between the control sources and the primary sources does not greatly affect the amount of reduction in acceleration level that can be achieved.

The effect of the circumferential location of control sources in cylindrical structures has been briefly investigated in this thesis, and is significant. Control sources are most effectively used when located at different circumferential spacings where each control source affects different circumferential modes of vibration. The circumferential location of the error sensors has not been investigated here, but it is suggested that the error sensors should be similarly unevenly spaced circumferentially.

REFERENCES

Aksu, G. and Ali, R. (1976) "Free vibration analysis of stiffened plates using the finite difference method", *Journal of Sound and Vibration*, **48**, 15-25.

Arnold R. N. and Warburton, G. B. (1951) "The flexural vibrations of thin cylinders", *Proceedings of the Institution of Mechanical Engineers*, **167**, 62-80.

Bailey, T. and Hubbard, J. E. (1985) "Distributed piezoelectric-polymer active vibration control of a cantilever beam", *Journal of Guidance, Control, and Dynamics*, **8**(5), 605-611.

Balas, M. J. (1978) "Active control of flexible structures", *Journal of Optimisation Theory and Applications*, **25**(3), 415-436.

Balas, M. J. and Canavin, J. R. (1977) "An active modal control system philosophy for a class of large space structures", *Proceedings of the First VPI & SU/AIAA Symposium on Dynamics and Control of Large Flexible Spacecraft*, Blacksburg, Virginia, 271-285.

Baz, A. and Poh, S. (1988) "Performance of an active control system with piezoelectric actuators", *Journal of Sound and Vibration*, **126**(2), 327-343.

Baz, A. and Poh, S. (1990) "Experimental implementation of the modified independent modal space control method", *Journal of Sound and Vibration*, **139**(2), 133-149.

Bogner, F. K., Fox, R. L. and Schmit, L. A. (1967) "A cylindrical shell discrete element", *AIAA Journal*, **5**(4), 745-750.

Burke, S. E. and Hubbard, J. E. (1988) "Distributed actuator control design for flexible beams", *Automatica*, **24**(5), 619-627.

Cantin, G. and Clough, R. W. (1968) "A curved, cylindrical shell, finite element", *AIAA Journal*, **6**(6), 1057-1062.

Cheng, S. P. and Dade, C. (1990) "Dynamic analysis of stiffened plates and shells using spline Guass collocation method", *Computers and Structures*, **36**(4), 623-629.

Cheng, S. P. and Jian-Guo, W. (1987) "Vibration analysis of flat shells by using B spline functions", *Computers and Structures*, **25**(1), 1-10.

Clark, R. L. and Fuller, C. R. (1992) "Optimal placement of piezoelectric actuators and polyvinylidene fluoride error sensors in active structural acoustic control approaches", *Journal of the Acoustical Society of America*, **92**(3), 1521-1533.

Clark, R. L. and Fuller, C. R. (1994) "Active control of structurally radiated sound from an enclosed finite cylinder", *Journal of Intelligent Material Systems and Structures*, **5**(3), 379-391.

Clark, R. L., Fuller, C. R. and Wicks, A. (1991) "Characterisation of multiple piezoelectric actuators for structural excitation", *Journal of the Acoustical Society of America*, **90**(1), 346-357.

Conover, W. (1956) "Fighting noise with noise", *Noise Control*, **92**(2), 78-82.

Cox, D. E. and Lindner, D. K. (1991) "Active control for vibration suppression in a flexible beam using a modal domain optical fiber sensor", *Journal of Vibration and Acoustics*, **113**, 369-382.

Crawley, E. F. and de Luis, J. (1987) "Use of piezoelectric actuators as elements of intelligent structures", *AIAA Journal*, **25**(10), 1373-1385.

Cremer, L., Heckl, M. and Ungar, E. E. (1973) "Structure Borne Sound", *Springer-Verlag*, Berlin.

Dimitriadis, E. K. and Fuller, C. R. (1989) "Investigation on active control of sound transmission through elastic plates using piezoelectric actuators", *AIAA Paper 89-1062*, AIAA 12th Acoustics Conference

Dimitriadis, E. K., Fuller, C. R. and Rogers, C. A. (1991) "Piezoelectric actuators for distributed vibration excitation of thin plates", *Journal of Vibration and Acoustics*, **113**, 100-107.

Elliott, S. J., Nelson, P. A., Stothers, I. M. and Boucher, C. C. (1989) "Preliminary results of in-flight experiments on the active control of propeller-induced cabin noise", *Journal of Sound and Vibration*, **128**(2), 355-357.

Fansen, J. L. and Chen, J. C. (1986) "Structural control by the use of piezoelectric active members", *Proceedings of NASA/DOD Control-Structures Interaction Conference*, NASA CP 2447, Part II.

Flügge, W. (1934) "Statik und Dynamik der Schalen".

Flügge, W. (1960) "Stresses in Shells", *Springer-Verlag*, Berlin.

Forsberg, K. (1964) "Influence of boundary conditions on the modal characteristics of thin cylindrical shells", *AIAA Journal*, **2**(12), 2150-2157.

Forsberg, K. (1966) "A review of analytical methods used to determine the modal characteristics of cylindrical shells", *NASA CR - 613*.

Fuller, C. R. (1981) "The effects of wall discontinuities on the propagation of flexural waves in cylindrical shells", *Journal of Sound and Vibration*, **75**(2), 207-228.

Fuller, C. R. (1990) "Active control of sound transmission/radiation from elastic plates by vibration inputs: I. analysis", *Journal of Sound and Vibration*, **136**(1), 1-15.

Fuller, C. R. and Jones, J. D. (1987) "Experiments on reduction of propeller induced interior noise by active control of cylinder vibration", *Journal of Sound and Vibration*, **112**(2), 389-395.

Fuller, C. R., Gibbs, G. P. and Gonidou, L. O. (1990) "Application of power and impedance measurement techniques to the study of active control of flexural energy flow in beams", *Proceedings of the Third International Congress on Intensity Techniques*, 389-396.

Fuller, C. R., Hansen, C. H. and Snyder, S. D. (1989) "Active control of structurally radiated noise using piezoceramic actuators", *Inter-noise '89*, 509-512.

Galletly, G. D. (1954) "On the in-vacuo vibrations of simply supported ring stiffened cylindrical shells", *Proceedings of the 2nd U. S. National Congress on Applied Mechanics*, 225-231.

Gibbs, G. P. and Fuller, C. R. (1990) "Experiments on active control of vibrational power flow using piezoceramic actuators and sensors", *AIAA conference*.

Gibbs, G. P. and Fuller, C. R. (1993) "A `real time' wave vector filter for one dimensional structural media", *Proceedings of the Fourth International Congress on Intensity Techniques*, 127-136.

Gonidou, L. O. (1988) "Active Control of Flexural Power Flow in Elastic Thin Beams", *Master of Science Thesis, Virginia Polytechnic Institute and State University*.

Graff, K. F. (1975) "Wave Motion in Elastic Solids", *Clarendon Press*, Oxford.

Guicking, D. (1990) "On the invention of active noise control by Paul Lueg", *Journal of the Acoustical Society of America*, **87**(5), 2251-2255.

Gupta, B. V. R., Ganesan, N. and Narayanan, S. (1986) "Finite element free vibration analysis of damped stiffened panels", *Computers and Structures,* **24**, 485-489.

Halkyard, C. R. and Mace, B. R. (1993) "A wave component approach to structural intensity in beams", *Proceedings of the Fourth International Congress on Intensity Techniques*, 183-190.

Haung, Y. Y. (1991) "Orthogonality of wet modes in coupled vibrations of cylindrical shells containing liquids", *Journal of Sound and Vibration*, **145**(1), 51-60.

Henshell, R. D., Neale, B. K. and Warburton, G. B. (1971) "A new hybrid cylindrical shell finite element", *Journal of Sound and Vibration*, **16**(4), 519-531.

Hϕjbjerg, K. (1991) "A new two-microphone impedance tube with improved microphone design for materials testing", *Brüel and Kjær*, Denmark.

Hoppmann, W. H. (1957) "Some characteristics of the flexural vibrations of orthogonally stiffened cylindrical shells", *Journal of the Acoustical Society of America*, **30**(1), 77-82.

Jones, J. D. and Fuller, C. R. (1987) "Active control of sound fields in elastic cylinders by vibration inputs", *Noise-Con '87*, 413-418.

Jones, J. D. and Fuller, C. R. (1989) "Active control of sound fields in elastic cylinders by multicontrol forces", *AIAA Journal*, **27**(7), 845-852.

Kim, S. J. and Jones, J. D. (1991) "Optimal design of piezoactuators for active noise and vibration control", *AIAA Journal*, **29**(12), 2047-2053.

Kirk, C. L. (1970) "Natural frequencies of stiffened rectangular plates", *Journal of Sound and Vibration*, **13**(4), 375-388.

Koko, T. S. and Olson, M. D. (1992) "Vibration analysis of stiffened plates by super elements", *Journal of Sound and Vibration*, **158**(1), 149-167.

Langley, R. S. (1992) "A dynamic stiffness technique for the vibration analysis of stiffened shell structures", *Journal of Sound and Vibration*, **156**(3), 521-540.

Leissa, A. W. (1969) "Vibration of Plates", *NASA SP-160*.

Leissa, A. W. (1973*a*) "Vibration of Shells", *NASA SP-288*.

Leissa, A. W. (1973*b*) "The free vibration of rectangular plates", *Journal of Sound and Vibration*, **31**(3), 257-293.

Lester, H. C. and Lefebvre, S. (1993) "Piezoelectric actuator models for active sound and vibration control of cylinders", *Journal of Intelligent Material Systems and Structures*, **4**, 295-306.

Liao, C. Y. and Sung, C. K. (1991) "Vibration suppression of flexible mechanisms using piezoelectric sensors and actuators", *Journal of Intelligent Material Systems and Structures*, **2**, 177-197.

Linjama, J. and Lahti, T. (1993) "Measurement of bending wave reflection and impedance in a beam by the structural intensity technique", *Journal of Sound and Vibration*, **161**(2), 317-331.

Mace, B. R. (1987) "Active control of flexible vibrations", *Journal of Sound and Vibration*, **114**(2), 253-270.

Mead, D. J. and Bardell, N. S. (1986) "Free vibration of a thin cylindrical shell with discrete axial stiffeners", *Journal of Sound and Vibration*, **111**(2), 229-250.

Mead, D. J. and Bardell, N. S. (1987) "Free vibration of a thin cylindrical shell with periodic circumferential stiffeners", *Journal of Sound and Vibration*, **115**(3), 499-520.

Mead, D. J., Zhu, D. C. and Bardell, N. S. (1988) "Free vibration of an orthogonally stiffened flat plate", *Journal of Sound and Vibration*, **127**(1), 19-48.

Mecitoglu, Z. and Dökmeci, M. C. (1991) "Free vibrations of a thin, stiffened, cylindrical shallow shell", *AIAA Journal*, **30**(3), 848-850.

Meirovitch, L. (1975) "Elements of Vibration Analysis", *M^c Graw-Hill*, New York.

Meirovitch, L. and Bennighof, J. K. (1986) "Modal control of travelling waves in flexible structures", *Journal of Sound and Vibration*, **111**(1), 131-144.

Meirovitch, L. and Norris, M. A. (1984) "Vibration control",8 *Inter-noise '84*, 477-482.

Meirovitch, L. and Öz, H. (1980) "Active control of structures by modal synthesis", *Structural Control*, North-Holland Publishing Company & SM Publications, 505-521.

Meirovitch, L., Baruh, H. and Öz, H. (1983) "A comparison of control techniques for large flexible systems", *Journal of Guidance, Control, and Dynamics*, **6**(4), 302-310.

Metcalf, V. L., Fuller, C. R., Silcox, R. J. and Brown, D. E. (1992) "Active control of sound transmission/radiation from elastic plates by vibration inputs, II: experiments", *Journal of Sound and Vibration*, **153**(3), 387-402.

Mikulas, M. M. and M^{c}Elman, J. A. (1965) "On free vibrations of eccentrically stiffened cylindrical shells and flat plates", *NASA TN D-3010*.

Morse, P. M. (1948) "Vibration and Sound", *M^{c}Graw-Hill*, New York.

Mukhopadhyay, M. (1978) "A semi-analytic solution for the free vibration of rectangular plates", *Journal of Sound and Vibration*, **60**(1), 71-85.

Mukhopadhyay, M. (1979) "Free vibration of rectangular plates with edges having different degrees of rotational restraint", *Journal of Sound and Vibration*, **67**(4), 459-468.

Mustafa, B. A. J. and Ali, R. (1987) "Free vibration analysis of multi-symmetric stiffened shells", *Computers and Structures*, **27**(6), 803-810.

Noiseux, D. U. (1970) "Measurement of power flow in uniform beams and plates", *Journal of the Acoustical Society of America*, **47**(2), 238-247.

Olson, H. F. (1956) "Electronic control of noise, vibration, and reverberation", *Journal of the Acoustical Society of America*, **28**(5), 966-972.

Olson, H. F. and May, E. G. (1953) "Electronic sound absorber", *Journal of the Acoustical Society of America*, **25**(6), 1130-1136.

Olson, M. D. and Hazell, C. R. (1977) "Vibration studies on some integral rib-stiffened plates", *Journal of Sound and Vibration*, **50**, 43-61.

Orris, R. M., and Petyt, M. (1974) "A finite element study of harmonic wave propagation in periodic structures", *Journal of Sound and Vibration*, **33**(2), 223-236.

Païdoussis, M. P., Misra, A. K. and Nguyen, V. B. (1992) "Internal- and annular-flow-induced instabilities of a clamped-clamped or cantilevered cylindrical shell in a coaxial conduit: the effects of system parameters", *Journal of Sound and Vibration*, **159**(2), 193-205.

Palazzolo, A. B., Lin, R. R., Alexander, R. M., Kascak, A. F. and Montague, J. (1989) "Piezoelectric pushers for active vibration control of rotating machinery", *Journal of Vibration, Acoustics, Stress, and Reliability in Design*, **111**, 298-305.

Pan, J. and Hansen, C. H. (1990*a*) "Active control of vibration in a beam", *Proceedings of The Australian Vibration and Noise Conference*, Monash University, Australia, 18-22.

Pan, J. and Hansen, C. H. (1990*b*) "Active control of total power flow along a beam", *Proceedings of the International Congress on Recent Developments in Air- and Structure-Borne Sound and Vibration*, Auburn University, USA, 229-236.

Pan, J., Hansen, C. H. and Snyder, S. D. (1992) "A study of the response of a simply supported beam to excitation by a piezoelectric actuator", *Journal of Intelligent Material Systems and Structures*, **3**, 3-16.

Pan, X. and Hansen, C. H. (1993*a*) "Effect of error sensor location and type on the active control of beam vibration", *Journal of Sound and Vibration*, **165**(3), 497-510.

Pan, X. and Hansen, C. H. (1993*b*) "Effect of end conditions on the active control of beam vibration", *Journal of Sound and Vibration*, **168**(3), 429-448.

Pan, X. and Hansen, C. H. (1994) "Piezoelectric crystal vs point force excitation of beams and plates", *Journal of Intelligent Material Systems and Structures*, **5**(3), 363-370.

Pan, X. and Hansen, C. H. (1995*a*) "Active control of vibratory power flow along a semi-infinite plate", *Journal of Sound and Vibration*, yet to be published.

Pan, X. and Hansen, C. H. (1995*b*) "Active control of vibration transmission in a cylindrical shell", *Journal of Sound and Vibration*, yet to be published.

Patel, J. S. and Neubert, V. H. (1970) "Natural frequencies and strain distribution in a ring-stiffened thick cylindrical shell", *Journal of the Acoustical Society of America*, **47**(2), 248-256.

Pavić, G. (1976) "Measurement of structure borne wave intensity, part I: formulation of the methods", *Journal of Sound and Vibration*, **49**(2), 221-230.

Petersson, B. A. T. (1993*a*) "Structural acoustic power transmission by point moment and force excitation, part I: beam- and frame-like structures", *Journal of Sound and Vibration*, **160**(1), 43-66.

Petersson, B. A. T. (1993*b*) "Structural acoustic power transmission by point moment and force excitation, part II: plate-like structures", *Journal of Sound and Vibration*, **160**(1), 67-91.

Redman-White, W., Nelson, P. A. and Curtis, A. R. D. (1987) "Experiments on the active control of flexural wave power flow", *Journal of Sound and Vibration*, **112**(1), 187-191.

Reismann J. (1968) "Response of a cylindrical shell to an inclined moving pressure discontinuity (shock wave)", *Journal of Sound and Vibration*, **8**(2), 240-255.

Reismann, H. and Pawlik, P. S. (1968) "Plane-strain dynamic response of a cylindrical shell - a comparison of three different shell theories", *Journal of Applied Mechanics*, **35**(2), 297-305.

Rivory, J. F. (1992) "Dynamic Response of Simply Supported Beams Excited by Piezoelectric Actuators", *Master of Science Thesis, University of Adelaide*.

Rivory, J. F., Hansen, C. H. and Pan, J. (1994) "Further studies of the dynamic response of a simply supported beam excited bya pair of our-of-phase piezoelectric actuators", *Journal of Intelligent Material Systems and Structures*, **5**, 654-664.

Romano, A. J., Abraham, P. B. and Williams, E. G. (1990) "A Poynting vector formulation for thin shells and plates, and its application to structural intensity analysis and source localisation. part I: theory", *Journal of the Acoustical Society of America*, **87**(3), 1166-1175.

Seybert, A. F. and Ross, D. F. (1977) "Experimental determination of acoustic properties using a two-microphone random-excitation technique", *Journal of the Acoustic Society of America*, **61**(5), 1362-1370.

Sinha, G. and Mukhopadhyay, M. (1994) "Finite element free vibration analysis of stiffened shells", *Journal of Sound and Vibration*, **171**(4), 529-548.

Smith, B. L. and Haft, E. E. (1968) "Natural frequencies of clamped cylindrical shells", *AIAA Journal*, **6**(4), 720-721.

Snyder, S. D. (1990) "A Fundamental Study of Active Noise Control System Design", *Ph.D. Thesis, University of Adelaide.*

Taylor, P. D. (1990) "Measurement of structural intensity, reflection coefficient, and termination impedance for bending waves in beams", *Proceedings of the Third International Congress on Intensity Techniques*, 249-256.

Thomas, D. R., Nelson, P. A. and Elliot, S. J. (1993*a*) "Active control of the transmission of sound through a thin cylindrical shell, part I: the minimization of vibrational energy", *Journal of Sound and Vibration*, **167**(1), 91-111.

Thomas, D. R., Nelson, P. A. and Elliot, S. J. (1993*b*) "Active control of the transmission of sound through a thin cylindrical shell, part II: the minimization of acoustic potential energy", *Journal of Sound and Vibration*, **167**(1), 113-128.

Timoshenko, S. (1959) "Theory of Plates and Shells", *M^c^Graw-Hill*, New York.

Trolle, J. L. and Luzzato, E. (1990) "Application of structural intensity for diagnostic in one dimension problems", *Proceedings of the Third International Congress on Intensity Techniques*, 397-404.

Tzou, H. S. and Fu, H. Q. (1994*a*) "A study of segmentation of distributed piezoelectric sensors and actuators, part I: theoretical analysis", *Journal of Sound and Vibration*, **172**(2), 247-259.

Tzou, H. S. and Fu, H. Q. (1994*b*) "A study of segmentation of distributed piezoelectric sensors and actuators, part I: parametric study and active vibration controls", *Journal of Sound and Vibration*, **172**(2), 261-275.

Tzou, H. S. and Gadre, M. (1989) "Theoretical analysis of a multi-layered thin shell coupled with piezoelectric shell actuators for distributed vibration controls", *Journal of Sound and Vibration*, **132**(3), 433-450.

von Flotow, A. H. (1986) "Travelling wave control for large spacecraft structures", *Journal of Guidance, Control, and Dynamics*, **9**(4), 462-468.

von Flotow, A. H. and Schäfer, B. (1986) "Wave-absorbing controllers for a flexible beam", *Journal of Guidance, Control, and Dynamics*, **9**(6), 673-680.

Wah, T. and Hu, W. C. L. (1967) "Vibration analysis of stiffened cylinders including inter-ring motion", *Journal of the Acoustical Society of America*, **43**(5), 1005-1016.

Wang, B., Dimitriadis, E. K. and Fuller, C. R. (1991) "Active control of structurally radiated noise using multiple piezoelectric actuators", *AIAA Journal*, **29**(11), 1802-1809.

Wang, C. T. (1953) "Applied Elasticity", *McGraw-Hill*, New York.

Warburton, G. B. (1969) "Comments on `Natural frequencies of clamped cylindrical shells'", *AIAA Journal*, **7**(2), 383-384.

Wu, J. R. and Liu, W. H. (1988) "Vibration of rectangular plates with edge restraints and intermediate stiffeners", *Journal of Sound and Vibration*, **123**(1), 103-113.

Yu, Y.-Y. (1955) "Free vibrations of thin cylindrical shells having finite lengths with freely supported and clamped edges", *Journal of Applied Mechanics*, **22**, 547-552.

Zhu, D. C. and Bardell, N. S. (1985) "On the hierarchical finite element technique", *Computational Structural Mechanics with Applications*, **2**(3), 1-10.

PUBLICATIONS ORIGINATING FROM THESIS WORK

PAPERS PUBLISHED IN AND SUBMITTED TO REFEREED JOURNALS

Young, A. J. and Hansen, C. H. (1994) "Control of flexural vibration in a beam using a piezoceramic actuator and an angle stiffener", *Journal of Intelligent Material Systems and Structures*, **5**(4), 536-549.

Young, A. J. and Hansen, C. H. (1994) "Control of flexural vibration in a stiffened plate using piezoceramic actuators and an angle stiffener", *Journal of Active Control*, yet to be published.

Young, A. J. and Hansen, C. H. (1995) "Control of flexural vibration in a stiffened cylinder using piezoceramic actuators and an angle stiffener", *Journal of Active Control*, yet to be published.

Young, A. J. and Hansen, C. H. (1995) "Control of flexural vibration in stiffened structures using multiple piezoceramic actuators", *Applied Acoustics*, yet to be published.

PAPERS PUBLISHED IN REFEREED CONFERENCE PROCEEDINGS

Hansen, C. H., Young, A. J. and Pan, X. (1993) "Active control of harmonic vibrations in beams with arbitrary end conditions", *Virginia Polytechnic Institute*.

Publications originating from thesis work

Young, A. J. and Hansen, C. H. (1993) "Experimental approximation of the impedance of an arbitrary beam termination", *Winter Annual Meeting of the American Society of Mechanical Engineers*, Paper No. 93-WA/NCA-1.

Hansen, C. H. and Young, A. J. (1994) "Active control of vibration transmission in a stiffened semi-infinite plate", *Third International Congress on Air- and Structure-Borne Sound and Vibration*.

Hansen, C. H. and Young, A. J. (1994) "Active control of vibration transmission in stiffened structures using piezoceramic actuators", *Inter•noise*.

Hansen, C. H. and Young, A. J. (1995) "Control of flexural vibration in a ring-stiffened cylinder using piezoceramic stack actuators", *Active '95*.