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A STUDY TO DEMONSTRATE THE POTENTIAL BENEFITS OF ACTIVE VIBRATION CONTROL IN THE ENGINEERING COMMUNITY

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Abstract. *Passive vibration damping is widely used in the engineering industry as a means of limiting vibration levels in order to reduce weight and increase life of components and systems. Whilst passive damping is very effective there still exists residual vibration that can be problematic especially within applications where minimum vibration levels are imperative. For this reason much research into relatively new concepts e.g. active vibration control has been undertaken in the last twenty years, [1, 2].*

Active vibration control uses the basic theory of destructive interference in order to annihilate a particular vibratory waveform. The method utilizes the principal of closed loop control in order to find a signal capable of producing this annihilation. At its most basic level active control is the superposition of two waves that are at the same frequency and amplitude but exactly out of phase. The resultant waveform is therefore zero. In order to achieve this in situations where the vibrating signal is a complicated modulation of several frequencies the control algorithm uses feedback in order to continually update the control signal and attain better results, [3].

In this work an experimental vibrating test-rig is demonstrated, its vibratory characteristics are given and a dominant mode of vibration is actively controlled by exciting the system in this state and phase synchronizing an actuator and a control actuator. The demonstration provides a useful tutorial in the simplistic physics behind active control and the discussion provides philosophical insight into the engineering implications that such control can provide.

1 INTRODUCTION

Active Control of Vibrations (AVC) is not a new concept, the theoretical benefits of destructive engineering have been known for a long time, however, advancements in computer science and developments in our engineering capabilities have meant that AVC has become more popular in recent years.

Destructive interference is the simple concept that if two waves collide with the same amplitude and exact opposite phase they will cancel each other out, this can be visualised in Figure 1.

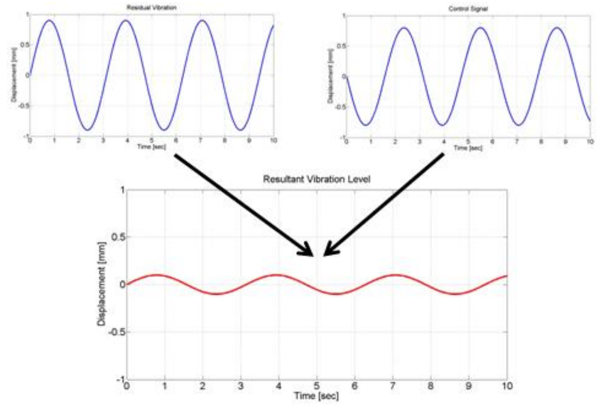

Figure 1: When two waves meet the resultant wave is minimal compared to the original two.

Early work on Active Control can be found as far back as the 1980’s. In [4] Burrows et al describe an active control experiment involving a rotor and a single magnetic actuator device.

In [1] Daley et al developed an active/passive hybrid mounting system and tested the results for marine applications on full test vessels. The mounting system was based on an electromagnet combined in parallel with passive elements. A feedback control method was developed based on minimizing a quadratic cost function that reduced the system resonances. For high frequency applications PZT (Piezo Zirconium Titaniate) technology has been shown to work well as a sensor – actuator pair device for active control. In [2] Moheimani provides a good review of PZT for such problems. Active technology is not restricted to structural vibration problems. In [3] Kuo and Morgan provide a tutorial in Active Noise Cancellation (ANC). This approach to uses the same methodology but for structural borne noise problems. The application field for such technology is wide and encompasses any industry that has problematic vibration levels that passive damping alone cannot take care of. In [5] Svaricek et al provide a number of examples where the automotive industry could and do benefit from AVC. In [6] Stanway, Rongong and Sims provide a good review of ACLD (Active Constrained Layer Damping) technology that uses the principles of active control and combined with passive technology provides a tool capable of vibration reduction. Many control algorithms have been tried and implemented including the LQR algorithm m in [7] and a method of feed-forward control in [8].

AVC is based on the principal of feedback. The open loop system can be characterised and the poles of the system (resonance) can be identified, Figure 2.

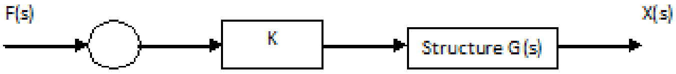

Figure 2: Open loop control.

The principal of feedback is implemented to monitor the phase angle between the two signals and ensure the optimum phase difference is in place, Figure 3.

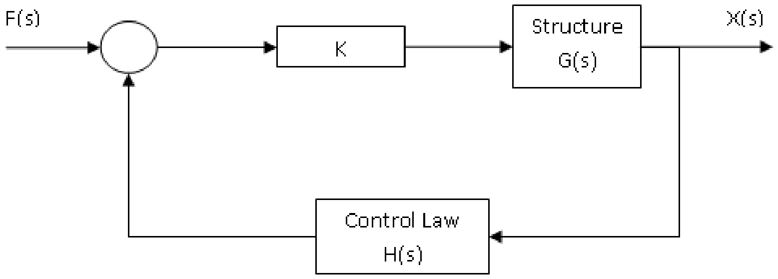

Figure 3: Closed loop control.

A simplistic approach would be to measure the acceleration and simply flip the signal in real–time; this would be achieved mathematically by multiplying the signal by -1, essentially a gain. Failing this, more sophisticated algorithms e.g. adaptive feedforward or PID algorithms can be investigated, a PID routine will be used in this paper.

The following work demonstrates the principal of destructive interference in a simple form. A generic test structure is described and excited and based on the principal of feedback the vibrating structure is actively controlled. Finally the engineering implications of this method are discussed.

2 PID CONTROL

A proportional – integral – derivative controller (PID) is a generic control loop feedback mechanism used for closed loop control of a system. It is based on the principal of a feedback loop, Figure 1. For a complete description of PID control and control theory the reader is referred to [9].

The input signal is the process variable, *u(t)*. The desired level for the process variable is called the set-point. The set-point level can be set by taking the RMS of the input signal and reducing this value by a prescribed amount, e.g. 20%. The input to the process is the manipulated variable (MV). The difference between the input measurement and the set-point level is the error (*e*), this quantifies whether the vibration level is too high and by how much.

The basic principle is then to measure the input, compare this to the set-point and depending on the error, either do nothing or adjust the signal accordingly to try and reduce the error! This approach is heuristic.

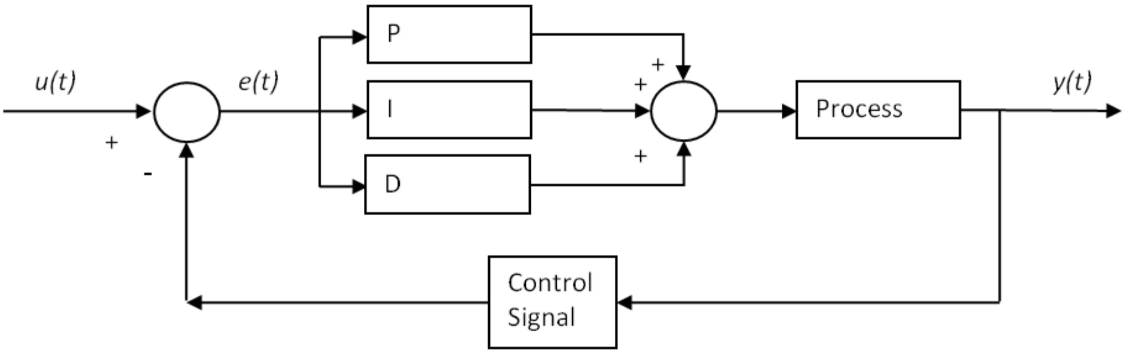

Figure 4: Closed loop control schematic of the PID operation.

Proportional control (P) will adjust the amplitude or gain of the shaker signal, integral control (I) will increase the rate of the process and derivative control can be thought of as a compensation parameter. The normal procedure is to apply PI control as a first solution then add derivative (D) as a slight adjustment parameter.

The PID control algorithm can be written mathematically in the time domain;

$$u(t) = MV(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t) \tag{1}$$

Where K_p is the proportional gain, a tuning parameter, K_i is integral gain, a tuning parameter, K_d is the derivative term, also a tuning parameter, e is the error, this amount is calculated by subtracting the set-point from the process variable and t is the time variable. This algorithm can also be expressed in frequency coordinates by making use of the Laplace transform;

$$G(s) = K_p + \frac{K_i}{s} + K_d s = \frac{K_d s^2 + K_p s + K_i}{s} \tag{2}$$

Rearranging Eq. 2 into the following form;

$$G(s) = K_d \frac{s^2 + \frac{K_p}{K_d} s + \frac{K_i}{K_d}}{s} \tag{3}$$

Makes determination of the closed loop transfer function a trivial matter;

$$H(s) = \frac{1}{s^2 + 2\varsigma\varpi_0 s + \varpi_0{}^2} \tag{4}$$

Therefore if;

$$\frac{K_i}{K_d} = \omega_0{}^2 \tag{5}$$

And,

$$\frac{K_p}{K_d} = 2\varsigma\varpi_0 \tag{6}$$

Then,

$$G(s)H(s) = \frac{K_d}{s} \tag{7}$$

This is a very useful formulation for the removal of poles, or system resonance.

3 EXPERIMENTAL SETUP

The test-rig for the active benchmark consists of a beam mounted at each end on rubber mounts. An excitation actuator in the form of an electro-dynamic shaker is placed at one end and a second control actuator is placed at the other. An accelerometer is placed near to the control device in order to assess its success in reducing the level of vibration on the beam. Figure 5 shows the test set up.

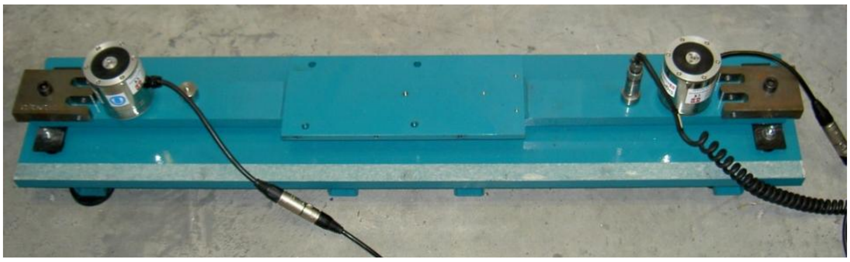

Figure 5: The beam test-rig: The shaker devices can be seen at either end of the beam. One is for the actuation and one is for the control.

The data acquisition set-up consists of National Instruments hardware, specifically a C-RIO 9113 device, and post processing is done using LabVIEW. The structure to be tested is a simple supported beam. The logic behind such a simple structure is to understand the techniques involved in a controlled laboratory setting before testing more complicated structures that can give more possible sources of uncertainty. A random excitation signal is transmitted through a power amplifier before causing a disturbance at the actuator. Alternatively some other form of signal generation could be used, e.g. a signal generator, the purpose is to cause vibratory motion of a structure. The response is measured using a PCB accelerometer sensor; this response signal is conditioned via an ICP sensor signal conditioner before being measured by the C-RIO system.

Simultaneously, a second accelerometer measures the response of the structure and sends this, same, signal to the controller via the National Instrument DAQ. The program then, based on the error calculation, decides on the feedback gains to be selected, in order to generate the active control signal. This signal is then sent to the controller actuator, situated on the structure. The process is shown schematically in Figure 6.

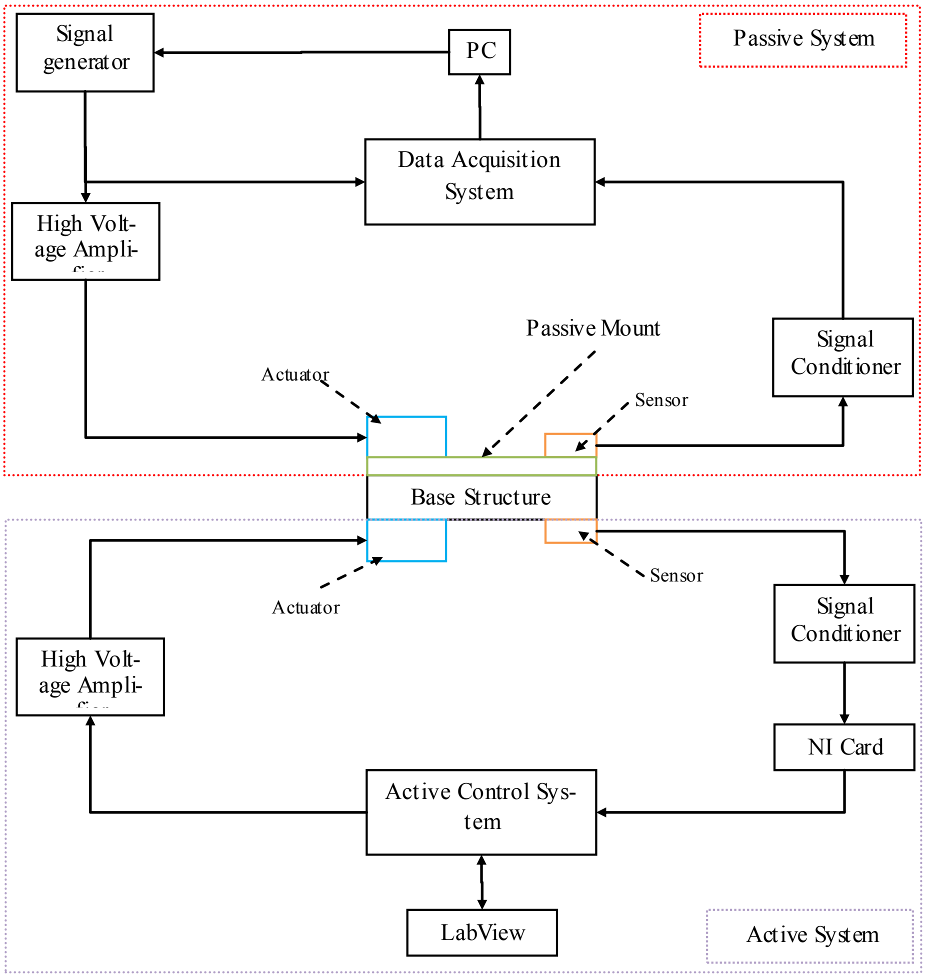

Figure 6: Flow chart demonstrating the stages involved in both active and passive control.

LabVIEW is needed to measure an acceleration signal, analyse the signal, run the signal through the PID program to select the PID gains and generate a control signal accordingly and send this signal to a shaker, in real time.

4 RESULTS AND DISCUSSION

Data is acquired in real time using a National Instruments Analogue Input device. The data is processed, high frequency noise is removed and aliasing is avoided via windowing the data. The data is then passed to the control algorithm and an analogue output signal is generated. This is passed to an actuation device.

A frequency analysis was performed on the beam in order to determine the dominant modes of vibration for active cancellation. The beam was excited with a random excitation signal low pass filtered with a cut off of 1000Hz. The response data was measured using an accelerometer at a sampling frequency of 2000Hz, (Figure 7), 18800 points of data were stored and a 1024 point FFT was applied to this data, Figure 8.

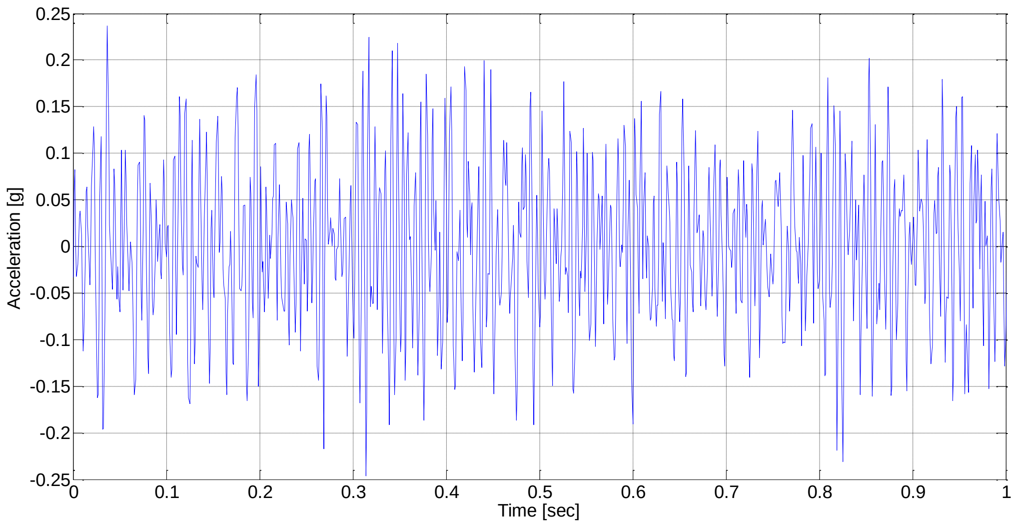

Figure 7: Response data for the beam due to a random excitation.

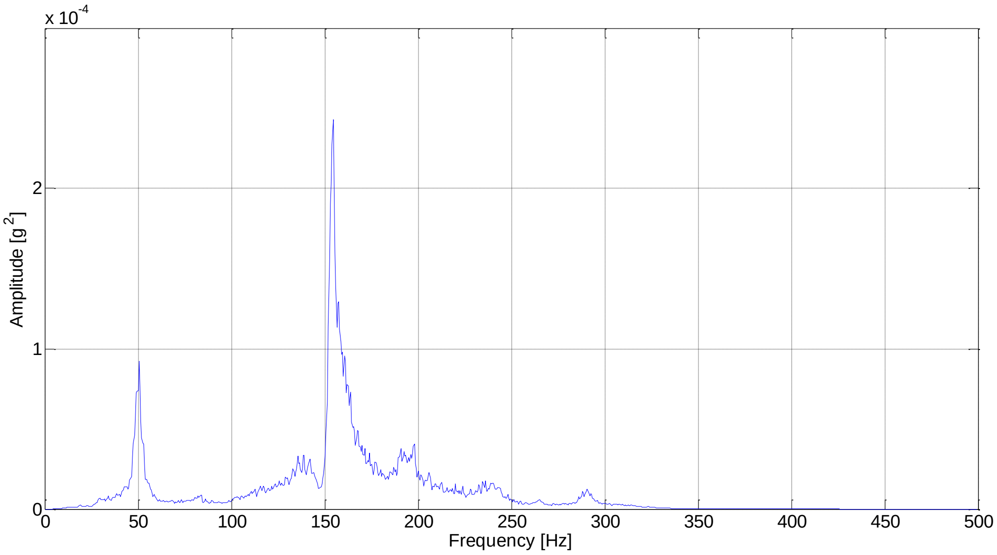

Figure 8: Results of a PSD analysis on a beam forced with a random excitation pattern.

It is clear from Figure 8 that the first dominant frequency exists at 50 Hz. The following analysis focuses on active control of this first mode. The beam was excited at 50Hz ensuring it is in a resonant condition. PID gains were selected to be P = 1, I = -0.01 and D = 0. The results are given in Figure 9.

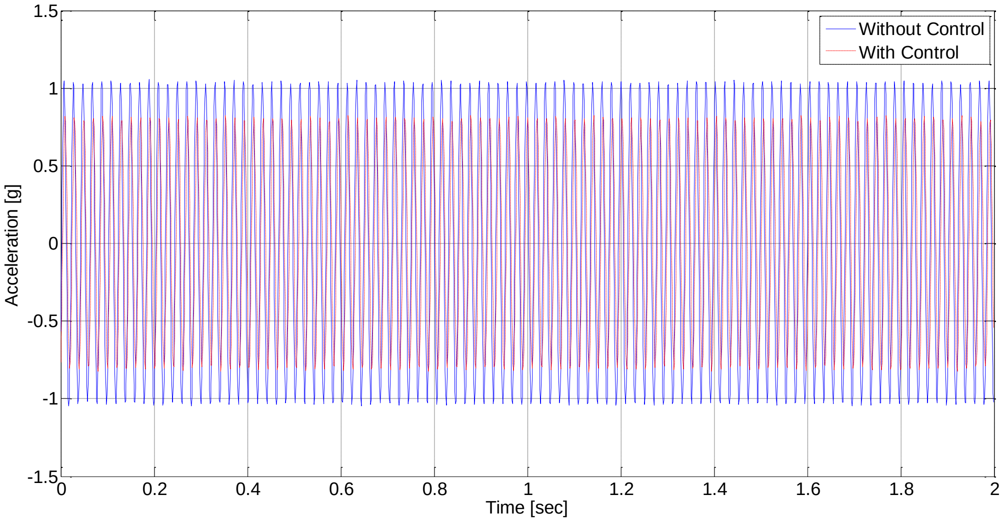

Figure 9: Results for the Active Control tests on the beam.

Finally the frequency response for the beam in the control on and off conditions is given. A 1024-point FFT response is shown in Figure 10. It is clear from these Figures that for the particular mode at 50Hz control has performed successfully.

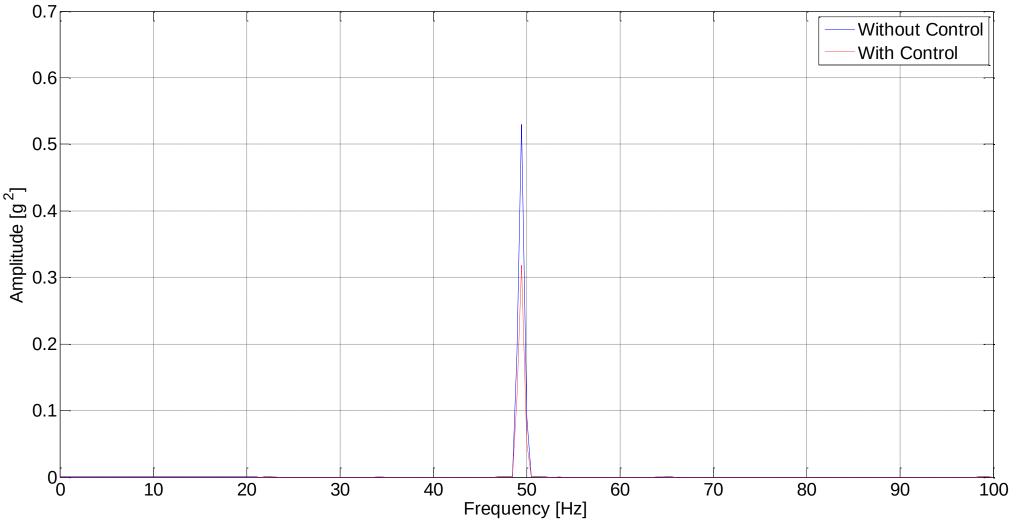

Figure 10: FFT response of the beam in the control on and off state.

This analysis, whilst being basic, offers proof that under the correct set of circumstances, AVC is indeed possible. It is imperative however that the forces involved in control and actuation are comparable. It is also essential that *a-priori* knowledge of the modeshape is known; only this way can the correct gains be selected for the feedback process. Initial care and attention can lead to control of the vibratory response and, in this case, a reduction in ~35% RMS acceleration level.

The ability to control vibration level offers an enhancement to existing technologies. Actuators come in various shapes and sizes. Devices such as PZT patches are incredibly small and lightweight. If the force of a particular problematic vibration was comparable to the force output potential from one of these patches, a solution to a problem is potentially at hand at relatively small size and weight cost, this could be advantageous to the aerospace industry. With the introductions of composite technologies vibration control in this manner is a possibility.

5 CONCLUSIONS

- This paper provides an introduction to active vibration control, a brief literature review is offered and the basic techniques that are needed to obtain vibration cancellation are discussed.
- A control strategy implementing a simplistic feedback loop is given and an experimental test rig is shown.
- Feedback control was used to successfully control structural vibration of a beam and the results are given.

REFERENCES

[1] S. M. Kuo and D. R. Morgan. *Active Noise Control: A Tutorial Review*. Proceedings of the IEEE, 87(6), 1999.

[2] R Stanway, J.A Rongong and N.D Sims. *Active constrained-layer damping: a state-of-the-art review.* Proc. Instn Mech. Engrs 217(I): J. Systems and Control Engineering.

[3] D. Inman, *Vibration with Control*. John Wiley and Sons, Ltd. ISBN: 0-470-01051-7. 2006.

[4] S.Daley, F.A. Johnson, J.B. Pearson, R.Dixon. *Active vibration control for marine applications*. Control Engineering Practice **12** (2004) 465–474.

[5] S. O. Reza Moheimani. *A Survey of Recent Innovations in Vibration Damping and Control Using Shunted Piezoelectric Transducers*. IEEE Transactions on Control Systems Technology, **11**(4), 2003.

[6] C. R. Burrows', M. N. Sahinkaya and S. Clements. *Active vibration control of flexible rotors: an experimental and theoretical study*. Proc. R. Soc. Lond. A 422, 123-146 (1989).

[7] F Svaricek, T Fueger, H-J Karkosch, P Marienfeld and C Bohn. *Automotive Applications of Active Vibration Control.* Vibration Control, ed Dr. Mickaël Lallart, ISBN 978-953-307-117-6, pp. 380, September 2010.

[8] Le, Shawn. Active vibration control of a flexible beam. (2009). Master's Theses. Paper 1983, (http://scholarworks.sjsu.edu/etd_theses/3983).

[9] G. Clark Smith. *Optimum Actuator Grouping in Feedforward Active Control Applications. Master's Theses*, October 6, 1994 Virginia Polytechnic Institute and State University.