EVOLUTIONARY OPTIMISATION AND REAL-TIME SELF-TUNING ACTIVE VIBRATION CONTROL OF A FLEXIBLE BEAM SYSTEM

MOHD SAZLI BIN SAAD

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

JANUARY 2014

EVOLUTIONARY OPTIMISATION AND REAL-TIME SELF-TUNING ACTIVE VIBRATION CONTROL OF A FLEXIBLE BEAM SYSTEM

MOHD SAZLI BIN SAAD

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

JANUARY 2014

In the name of Allah, Most Gracious, Most Merciful

To my beloved wife Wan Sallha Binti Yusoff, who are praying for me and who are provided me with support, help and encouragement that greatly contributed to the successful completion of my studies.

To my sons Muhammad Danish Irfan, Muhammad Dini Irsyad and Muhammad Razin Darwish, and to my daughter Damia Aleesya whose have brought wonderful fun, great motivation and bright inspiration into my life.

ACKNOWLEDGEMENT

Alhamdulillah, all praise is due to Allah S.W.T, the Most Beneficent and the Most Merciful, who has taught me what I knew not.

First and foremost, I wish to express special thanks, appreciation and deep gratitude to my main supervisor, Prof. Dr. Hishamuddin B. Jamaluddin, who has provide continuous guidance, advice, encouragement, support and generous amount of time in helping me to complete this research. His remarkable unique ways and professionalism of handling my weaknesses has turned my simplistic mind to see think in more rational and critical view. Special thanks also to Assoc. Prof. Dr. Intan Zaurah Bt. Mat Darus, my honourable co-supervisor, for her continuous guidance, committed support and invaluable advice throughout my study.

Sincere appreciation of course goes to my friends who give me unselfish support and my family especially my wife Wan Sallha Bt. Yusoff for their support and encouragement throughout in the completion of this research. Without their endless sacrifices, constant love and steadfast support, I would never have reach this level. To my sons Muhammad Danish Irfan, Muhammad Dini Irsyad and Muhammad Razin Darwish, and my daughter Damia Aleesya, it is to you I dedicate this effort.

Above all, I would like to offer my deepest appreciation and thanksgiving to Allah SWT. There is no way to measure what you've worth. You are The One who has made things possible. You deserve all glory and honor.

ABSTRACT

Active vibration control has long been recognised as a solution for flexible beam structure to achieve sufficient vibration suppression. The flexible beam dynamic model is derived according to the Euler Bernoulli beam theory. The resonance frequencies of the beam are investigated analytically and the validity was experimentally verified. This thesis focuses on two main parts: proportional-integral-derivative (PID) controller tuning methods based on evolutionary algorithms (EA) and real-time self-tuning control using iterative learning algorithm and pole-placement methods. Optimisation methods for determining the optimal values of proportional-integral-derivative (PID) controller parameters for active vibration control of a flexible beam system are presented. The main objective of tuning the PID controller is to obtain a fast and stable system using EA such as genetic algorithm (GA) and differential evolution (DE) algorithms. The PID controller is tuned offline based on the identified model obtained using experimental input-output data. Experimental results have shown that PID parameters tuned by EA outperformed conventional tuning method in term of better transient response. However, in term of vibration attenuation, the performance between DE, GA and Ziegler-Nichols (ZN) method produced about the same value. For real-time self-tuning control, successful design and implementation has been accomplished. Two techniques, self-tuning using iterative learning algorithm and self-tuning pole-placement control were implemented to adapt the controller parameters to meet the desired performances. In self-tuning using iterative learning algorithm, its learning mechanism will automatically find new control parameters. Whereas the self tuning pole-placement control uses system identification in real time and then the control parameters are calculated online. It is observed that self-tuning using iterative learning algorithm does not require accurate model of the plant and control the vibration based on the reference error, but it is unable to maintain its transient performance due to the change of physical parameters. Meanwhile, self-tuning pole-placement controller has shown its ability to maintain its transient performance as it was designed based on the desired closed loop poles where the control system can track changes in the plant and disturbance characteristics at every sampling time. Overall results revealed the effectiveness of both control schemes in suppressing the unwanted vibration over conventional fixed gain controllers.

ABSTRAK

Kawalan getaran aktif telah lama diakui sebagai penyelesaian kepada struktur rasuk lentur bagi mencapai penindasan getaran yang berkesan. Model dinamik rasuk lentur diperoleh berdasarkan kepada teori rasuk Euler Bernoulli. Frekuensi salunan juga diselidik secara analitik dan disahkan secara uji kaji. Tesis ini memfokus kepada dua bahagian utama; kaedah talaan pengawal terbitan kamiran berkadaran (PID) berasaskan kepada algoritma evolusi (EA) dan kaedah kawalan talaan-diri masa nyata dengan menggunakan algoritma pembelajaran berlelaran dan perletakan-kutub. Kaedah pengoptimuman dalam menentukan nilai optimum bagi parameter pengawal PID untuk mengawal getaran aktif sistem struktur rasuk lentur ditunjukkan. Objektif utama adalah untuk mendapatkan sistem yang stabil dan cepat melalui talaan pengawal PID dengan menggunakan EA seperti algoritma genetik (GA) dan evolusi kebezaan (DE). Pengawal PID ditala secara luar-talian berasaskan kepada model yang dikenal pasti dan diperoleh dengan menggunakan data uji kaji masukan-keluaran. Keputusan uji kaji telah menunjukkan PID yang ditala dengan EA telah mengatasi kaedah talaan secara konvensional dari segi sambutan fana. Walau bagaimanapun, dari segi pengecilan getaran, prestasi antara DE, GA dan kaedah Ziegler-Nichols (ZN) menghasilkan nilai yang lebih kurang sama. Bagi kawalan talaan-diri masa nyata, reka bentuk dan pelaksanaan telah berjaya dilakukan. Dua teknik, talaan-diri dengan menggunakan algoritma pembelajaran berlelaran dan talaan-diri kawalan perletakan-kutub dilaksanakan bagi menyesuaikan parameter pengawal dalam memenuhi prestasi yang dikehendaki. Dalam talaan-diri menggunakan algoritma pembelajaran berlelaran, mekanisme pembelajaran secara automatik akan mencari parameter kawalan baru. Manakala talaan-diri kawalan perletakan-kutub dengan menggunakan pengenalpastian sistem dalam masa nyata dan kemudian parameter kawalan dikira secara dalam-talian. Daripada pemerhatian didapati bahawa talaan-diri menggunakan algoritma pembelajaran berlelaran tidak memerlukan model yang tepat untuk loji dan mengawal getaran berdasarkan kepada ralat rujukan, tetapi ia tidak dapat mengekalkan prestasi fana kerana berlaku perubahan parameter fizikal. Sementara itu, talaan-diri kawalan perletakan-kutub telah menunjukkan keupayaan untuk mengekalkan prestasi fana kerana ia direka bentuk berdasarkan kutub gelung tertutup yang diingini di mana sistem kawalan boleh mengesan perubahan dalam ciri-ciri loji dan gangguan pada setiap masa pensampelan. Keputusan keseluruhan menunjukkan keberkesanan kedua-dua skim kawalan dalam menindas getaran yang tidak diingini terhadap pengawal konvensional gandaan tetap.

TABLES OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADC	-	Analog to digital converter
AFC	-	Active Force Control
ANFIS	-	Adaptive neuro-fuzzy inference systems
ANN	-	Artificial neural network
AR	-	Auto-regressive
ARMAX	-	Auto-regressive Moving Average with Exogenous
ARX	-	Auto-regressive with Exogenous
AVC	-	Active vibration control
DAC	-	Digital to analog converter
DAQ	-	Data acquisition
DE	-	Differential evolution
DOF	-	Degree of freedom
EA	-	Evolutionary algorithm
EP	-	Evolutionary programming
EPAS	-	Electric power assisted steering system
ES	-	Evolution strategies
FD	-	Finite difference
FDM	-	Finite difference method
FEM	-	Finite element method
GA	-	Genetic algorithm
GUI	-	Graphical user interface
ILA	-	Iterative learning algorithm
ILC	-	Iterative learning control
ILP	-	Self-tuning proportional using iterative learning algorithm
ILPID	-	Self-tuning proportional integral derivative using iterative learning algorithm
LQR	-	Linear quadratic regulator

LTI	-	Linear time-invariant
MFLAC	-	Model-free learning adaptive control
MIMO	-	Multiple input multiple outputs
MODE	-	Multi-objective differential evolution
MPPF	-	Modified positive position feedback
MSE	-	Mean square error
NI	-	National Instruments
NN	-	Neural network
ODE	-	Ordinary differential equation
P	-	Proportional
PC	-	Personal computer
PD	-	Proportional derivative
PDE	-	Partial differential equations
PDE	-	Partial differential equations
PID	-	Proportional integral derivative
PID-AFC	-	Proportional integral derivative active force control
PRBS	-	Pseudo random binary sequence
PSO	-	Particle swarm optimisation
PZT	-	Piezo material lead zirconate titanate
RLS	-	Recursive least square
SMC	-	Sliding mode controller
STPPC	-	Self-tuning pole placement control
TCSC	-	Thyristor controlled series compensator
TRMS	-	Twin rotor multi-input multi-output system
VI	-	Virtual instrument
ZN	-	Ziegler - Nichols

LIST OF SYMBOLS

A	-	Cross section area
$A(z^{-1})$, $B(z^{-1})$	-	Discrete system polynomials
a, b	-	Unknown system parameter to be identified
a_j	-	Lower bound
b_j	-	Upper bound
$C(z^{-1})$	-	Discrete disturbance polynomial
CR	-	Crossover constant
$d(t)$	-	Disturbance signal
E	-	Young's Modulus
e_k	-	System error
$\varepsilon(k)$	-	Model prediction error
f	-	Frequency (Hz)
F	-	Mutation constant
$F(z^{-1})$, $G(z^{-1})$	-	Discrete controller polynomials
f_1, g_0, g_1	-	Controller parameter in STPPC
G	-	Generation
I	-	Moment of inertia
K	-	Controller parameter gain
k_d	-	Derivative gain
k_i	-	Integral gain
K_{n+1}	-	New controller pa ameter gain
k_p	-	Proportional gain
L	-	Length of the beam
m	-	Mass
m_j	-	Number of bits
μ	-	Beam constant
n_a, n_b, n_c	-	Polynomials order

NP	-	Population size
$P(k)$	-	Covariance matrix
P_c	-	Crossover rate
P_m	-	Mutation rate
S	-	Stiffness matrix
t	-	Time
Δt	-	Time steps
$T(z^{-1})$	-	Characteristic equation
$u(t)$	-	Input signal
$U(x,t)$	-	Actuating force applied at a distance, x, from its fixed end at time, t
$v_{j,G}$	-	Target vector
$v_{j,G+1}$	-	Trial vector
x	-	Distance
Δx	-	Length segment
$x_{j,G}$	-	Random vector
$y(t)$	-	Output signal
$y(x,t)$	-	Beam's deflection at a distance, x, from its fixed end at time, t
y_d	-	Desired output
y_k	-	Actual output
$\hat{y}(k)$	-	Estimated model output
λ_l, λ_l*	-	l-th discrete complex conjugate pair
ρ	-	Density
Φ	-	Proportional learning parameter
β_n	-	Eigenvalue
ζ_l	-	Damping ratio
ω	-	Frequency (rad/s)
ω_{nl}	-	l-th natural frequency

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Vibrations and dynamic chaos are undesired phenomenon in structures. They cause disturbance, discomfort, damage and destruction of the system or the structure. The problem of vibration has been reported in many applications including automotive, aircraft, electrical machinery and civil structures. Vibration occurs whenever a mechanical mechanism is moved intentionally or unintentionally. The unwanted vibration may cause damage to structures or degradation to system's performance. Therefore, many attempts have been proposed to reduce this unwanted disturbance by considering passive and active controls. The simplest strategy is to make the structure more rigid so that the vibration can be resisted, but this may cause weight penalty and is not always acceptable. Another common approach is by using passive vibration control methods by mounting passive material such as vibration dampers or the dynamic absorber. Unfortunately, this method only works well at high frequencies or in a narrow frequency range but often have the disadvantage of added weight and poor low frequency performance. Furthermore, in many applications it is desirable to keep the weight as low as possible, which can make passive solutions unattractive (Christopher, 2007). In fact, it is a growing trend in manufacturing of engineering systems to reduce the weight of mechanical structures. This is particularly so in spacecraft and aircraft engineering, where it is possible to substantially decrease costs by use of lighter materials and/or weaker structures. However, this will in turn lead to even more flexible structural dynamics which may limit the performance of the structure.

In contrast with passive vibration control, an active vibration control is more effective, reliable, and flexible where the actuator can be adjusted according to the characteristic of vibration during operation. The potential of active vibration control (AVC) has received extensive attention in recent years due to the rise of many applications requiring effective vibration suppression systems such as in aerospace structures, hard disk drives, flexible robot arms, and micro-mechanical systems.

The concept of AVC was initially proposed by Lueg (1936) for noise cancellation. The aim of AVC is to reduce the amplitude of vibration of a dynamic system. It works based on artificially generating the cancellation signal to absorb the unwanted disturbance force that can reduce the effect of vibration to the system. Vibration suppression in AVC can be achieved by detecting and processing via suitable control schemes, thus the superimposed disturbance signals will cancel out the actual disturbance force. This is found to be more efficient and economical than passive control method especially at low frequency vibration suppression. Furthermore, AVC method offers a flexibility to control the unwanted vibrations with broad band frequencies with some modification on the control algorithms. As a result, AVC of flexible structures has attracted many attentions amongst researchers and engineers.

Due to the advance in theory and practice, the flexible structure has the ability to sustain with complex environments. A number of strategies based on conventional control and intelligent control scheme have been proposed in AVC system such as direct velocity feedback control, positive feedback control, *H* infinity control, sliding mode control, fuzzy control, adaptive control, self-tuning control, neural network control (Eski and Yildirim, 2009; Liang *et al.*, 2011; Mahmoodi and Ahmadian, 2009; Marinaki *et al.*, 2010; Salleh and Tokhi, 2010; Shin *et al.*, 2012; Zhi-cheng *et al.*, 2009). Recent development of AVC is briefly reviewed in Chapter 2.

1.2 Problem statement

Vibration reduction is a critical problem related to flexible structures especially in the application of aerospace application and robotics system, which often employs flexible structures that generally light weight and have relatively low damping for the fundamental and initial model. Furthermore, the frequency associated with these models are low, the vibration control of nodes become an important issue in light flexible structures. Active vibration control has been used as a solution for flexible structures to achieve sufficient vibration suppression for required precision accuracy.

With the emergence of smart materials such as a piezoelectric patch, the studies in active vibration control become more attractive. This is because smart materials offer low energy consumption, can be small in size, have fast response and can be integrated with the structures (Preumont, 2011b). In the case of active vibration control of flexible structures, such a piezoelectric material is normally bonded onto the structure which acts an actuator or sensor. Hence, it will add complexity to the analysis and modeling of the system.

Control strategies of flexible structures often depend on adequate modeling of the system dynamics. Many analytical model based approaches have been proposed to establish the physical model of the system behavior for a structure embedded with PZT such as finite element analysis, dynamic analysis of the modal response and etc. (Narayanan and Balamurugan, 2003; Tehrani *et al.*, 2011; Wang *et al.*, 2011b; Zhi-cheng *et al.*, 2009). However, those approaches are less effective under high precision system because of the difficulty in simulating the properties for such complicated system and sometimes, hindered by factors such as assuming perfect bonding between the structure and its actuator, and high computation time (Ezhilarasi *et al.*, 2006).

In addition, the assumption is contradictory to reality because of some special difficulties which involve, for example unmodeled dynamics of the flexible beam, component degradation, changing payload, changing structure parameters, etc. can destabilize a conventional fixed parameter control strategy (Kumar *et al*., 2006). Therefore, it is necessary to search for a good model of the flexible structure in order to obtain a better control performance. Suitable modelling of a dynamic system such a flexible structure, may results in good control (Darus and Al-Khafaji, 2012; Tavakolpour *et al.*, 2010b)

Thus, in this research, experimental study based on self-tuning control schemes was conducted in such a way that a real-time computer control can be applied to demonstrate the performances of the proposed control schemes. The three groups of vibration control schemes employed in this research are PID tuning using evolutionary algorithm based, self-tuning iterative learning algorithm based, and self-tuning pole-placement control. In PID tuning evolutionary algorithm (EA) based, PID is tuned by EA based on the estimated model using recursive least square technique. Then for self-tuning iterative learning algorithm based, the controller is tuned based on the error between the required set point and the actual value regardless to the knowledge of the system. Finally, for self-tuning pole-placement control, the controller is tuning online as the dynamic changes occur on the system itself or from the external disturbances. The performance of these control schemes are analysed separately via real-time PC-based computer control.

1.3 Objectives of the study

This research focuses on the practical implementation of AVC schemes via real-time PC-based computer control for flexible beam system by understanding and proving the behavior of smart structure under control strategy. Hence, three important objectives are stated below:

1. To develop PID controller tuning strategies using evolutionary algorithm that can effectively suppress the unwanted vibration on a flexible beam system.

2. To investigate the performance of active vibration control using real-time self-tuning control in suppressing the unwanted vibration on a flexible beam system under variation of disturbance excitation and system parameter.

3. To perform comparative assessment between self-tuning PID control and self-tuning pole-placement control schemes.

1.4 Scope of the study

The scope of the research is as follows:

1. In this study, the evolutionary algorithms considered to tune PID controller are genetic algorithm and differential evolution. The performance of the controller in suppressing the vibration is investigated based on the most dominant mode of frequency obtains from the resonance test.

2. The real-time self-tuning control schemes are based on the self-tuning of proportional and PID control using iterative learning algorithm and self-tuning pole-placement control schemes.

3. The robustness test for the proposed self-tuning control schemes are limited to variation of disturbance amplitude and beam tip load.

4. The comparative study between self-tuning of PID control using iterative learning algorithm (ILPID) and self-tuning pole-placement control (STPPC) highlight the performance of each control scheme in terms of settling time, actuator voltage dynamic behavior and vibration attenuation with regard to applied disturbance.

5. The graphical user interface is developed for online parameter adjustment, data saving and displaying the time response and frequency response on the actual vibration on a flexible beam.

1.5 Research contributions

A brief outline of the main contributions of this research is given in this subsection as follows:

1. This research provides details implementation of proportional integral derivative (PID) controller tuning via evolutionary algorithm (EA) (i.e. genetic algorithm and differential evolution) that optimally suppress the vibration of a flexible beam system using piezoelectric (PZT) actuator. This new approach allows the PID parameters to be tuned based on the identified model from a real plant using parametric system identification technique, which represents the dynamic characteristic of the system incorporated with smart materials i.e. PZT, and avoid the tangled mathematic or physical model development. The validity of the estimated model is validated by comparing its natural frequency of the dominant modes with the actual natural frequency. Test results show that the new approach of an proportional integral derivative (PID) controller tuning via evolutionary algorithm (EA) outperform the conventional tuning methods (i.e. Ziegler Nichols) in terms of transient response.

2. This research provides the outcomes from the experimental of AVC in flexible beam system using self-tuning control scheme based on ILA with a simple design approached run with graphical user interface (GUI) using LabVIEW programming. Its offers great advantageous in terms of vibration suppression, and robustness to the change of disturbance. In this study, the stopping criterion error based on the deflection of the beam is introduced in order to stop the learning process when the criterion is met. GUI has allowed online parameter adjustment and vibration monitoring of the actual process.

3. Active vibration control is performed using online self-tuning pole-placement control (STPPC) of a flexible beam system which is designed with a simple model structure Auto-Regressive with Exogenous Input (ARX) model. This simple structure offers several advantages which are easy to implement in real-time and reduce computation time where the overall computational task can be performed effectively. The controller is executed on real-time personal

computer (PC) based control. The implementation of self-tuning algorithm in LabVIEW programming is briefly explained. Its graphical user interface (GUI) was developed in such a way that user can perform online monitoring and manipulation of control parameters that are part of the active vibration control (AVC) of a flexible beam system. Results showing the transient performance between the self-tuning controller and a fixed controller due to a load change on a flexible beam. Self-tuning algorithm developed in mathscript coding integrated with the graphical programming language, G, in LabVIEW is briefly explained.

1.6 Methodology of the Study

After literature review has been carried out, the simulation model of the beam is developed using finite difference method. The modeling is done using suitable programming environment. The deflection of the beam can be observed dynamically at a finite duration of time. The simulated model is validated by comparing its resonance modes with the experimental values.

In order to demonstrate the practicality of the proposed control scheme, an experimental rig is developed. The vibration of the beam is measured using laser displacement sensor where the signal is transmitted to a data acquisition card for analog-to-digital conversion of the signal. The control algorithms will compute the amount of piezo-actuator voltage to suppress the vibration of the beam. The input voltage that is sent to the piezo-actuator need to be amplified by an amplifier, so that it can be operated sufficiently. The disturbance force is excited vertically at the free-end of the beam as a point force by using a piezo-actuator. Finally, real-time monitoring and control can be established directly from the computer system. The performance of the proposed controllers in attenuating the unwanted vibration is then investigated.

Then, resonance test is conducted via simulation and experimentation in order to identify the resonance frequency of a flexible beam system. Results from this test will identify the dominant modes of natural frequency which is the frequency of interest in vibration control.

After validating the resonance frequency of a flexible beam, control strategies are developed experimentally for PID tuning using evolutionary algorithms, self-tuning using iterative learning algorithm, and self-tuning pole-placement control. All these control strategies are implemented in real-time computer control using LabVIEW programming software with GUI. This GUI is intended to be an interactive learning tool that will allow user to get a feeling for how the active vibration control can be monitored and controlled in a real world. The performance of each of the control schemes are compared with a conventional control, conventional tuning methods and fixed controller. A performance analysis is carried out to highlight the advantages and the drawbacks between the proposed control schemes and conventional methods.

Finally, a comparative study between self-tuning using iterative learning algorithm and self-tuning pole-placement control schemes were carried out and reported in this chapter. The main objective of the comparative study is to observe the difference in performance simultaneously and also to exploit the benefits of using the proposed strategies. The overall performance of the control schemes is concluded. The proposed research strategy in the form of a flow chart is graphically shown in Figure 1.1.

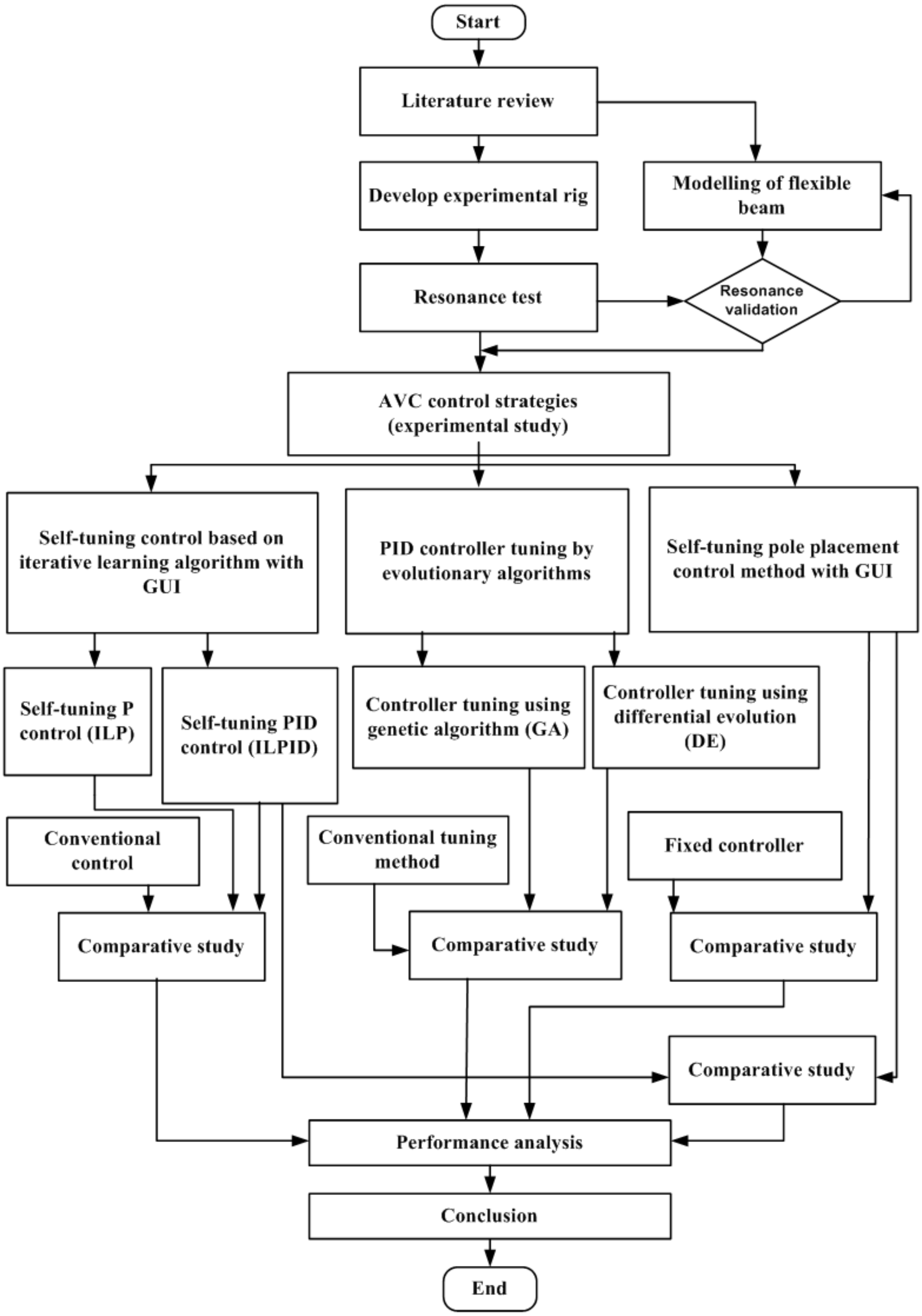

Figure 1.1: Research strategies flowchart

1.7 Organisation of the thesis

This thesis is organised into 7 chapters. A brief outline of contents of the thesis is as follows:

Chapter 1 presents an overview of the research problem. It involves the background and problem statement of the research as well as the objectives of the study and contributions. The methodology and flow chart of the thesis is also outlined in this chapter.

Chapter 2 is devoted to a literature study on AVC of the flexible structures. A brief overview of modeling approached based on finite different (FD) model is briefly reviewed. Then, recent applications of the proposed control schemes were highlighted. Finally the gaps between the proposed control schemes with the previous researcher are identified.

Chapter 3 presents the dynamic modelling and experimental setup of a flexible beam system. The dynamic equation of a flexible beam system is described and its corresponding simulation algorithm is developed. Then, experimental rig was developed to demonstrate the effectiveness of the proposed control scheme online via computer system. The experimental devices, experimental setup and method of capturing data are elaborated. The resonance test is carried out to find the dominant mode of the beam using the same types of excitation signal used in the simulation. Results from the experimental are compared with simulation and theoretical model where the accuracy of the measured and simulation frequencies is examined.

Chapter 4 presents a new approach of proportional integral derivative (PID) controller tuning via evolutionary algorithm (EA) that optimally suppress the vibration of a flexible beam system. This chapter starts with brief explanation of GA and DE in tuning the PID tuning controller. Then, those tuning methods were applied to tune the PID controller based on the identified flexible beam model. The benefits that it provides over conventional tuning method are illustrated.

Chapter 5 presents the development of self-tuning control using iterative learning algorithm for proportional and PID controller to suppress vibration of the flexible beam via real-time computer control. Before the implementation of the proposed controller on experimental rig, the working principle of ILA in tuning the controller parameter is observed via simulation environment. The effects of parameters in ILA such as learning parameter and stopping criterion to the control performance are presented. Then, the performance of self-tuning control schemes based on iterative learning algorithm is validated experimentally and compared with the conventional control schemes.

Chapter 6 presents the results of the online self-tuning pole-placement control scheme applied to control the vibration of a flexible beam via experimental rig. The performance of the controller is investigated by moving the pole location horizontally on the real axis of the z-plane. Then, the robustness of the proposed control scheme is tested by changing the physical parameter of the beam and comparisons are made with the results from a fixed gain controller. Finally, the performance between self-tuning using iterative learning and self-tuning pole-placement controls is demonstrated. The comparison between both control schemes revealed several findings which identifying the strengths and weaknesses of both of these control techniques.

The final chapter of this thesis, Chapter 7, summarises the work presented and draws relevant conclusions. Future works to the field of AVC of a flexible beam are discussed.

REFERENCES

Ahmad, S. M., Chipperfield, A. J. and Tokhi, M. O. (2002). Dynamic Modelling and Open-loop Control of a Twin Rotor Multi-input Multi-output System. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, 216 (6): 477-496.

Ahn, H. S., Chen, Y. and Moore, K. L. (2007). Iterative Learning Control: Brief Survey and Categorization. *IEEE Transactions on Systems, Man, and Cybernetics—Part C: Applications and Reviews*, 37 (6): 1099-1121.

Aldebrez, F. M., Alam, M. S. and Tokhi, M. O. (2005). Input-Shaping with GA-Tuned PID for Target Tracking and Vibration Reduction. *Proceedings of the International Symposium on Intelligent Control & 13th Mediterranean Conference on Control and Automation*, Limassol (Cyprus). 27-29 June 2005. 485-490.

Amor, J. (2007). Active Vibration Control of Flexible Structures using Delayed Position Feedback. *Systems and Amp; Control Letters*, 56 (3): 215-222.

Ariffin, A., Romlay, F. and Nor, M. (2003). Model Updating of Center Member Bar. *The 3rd International Conference on Numerical Analysis in Engineering, Pulau Batam, Indonesia*.

Arimoto, S., Kawamura, S. and Miyazaki, F. (1984). Bettering Operation of Robots By Learning. *Journal of Robotic Systems*, 1 (2): 123-140.

Arya, L. D., Verma, H. K. and Jain, C. (2011). Differential Evolution for Optimization of PID Gains in Automatic Generation Control. *International Journal on Computer Science and Engineering*, 3 (5): 1848-1856.

Astrom, K. J. and Hagglund, T. (1988). *Automatic Tuning of PID Controllers*: Instrument Society of America.

Astrom, K. J., Hagglund, T., Hang, C. C. and Ho, W. K. (1993). Automatic Tuning and Adaptation for PID Controllers - A Survey. *Control Engineering Practice*, 1 (4): 699-714.

Astrom, K. J. and Hagglund, T. (1995). *PID Controllers: Theory, Design, and Tuning*: Instruments Society of America.Åström, K. J. and Wittenmark, B. (1973). On Self Tuning Regulators. *Automatica*, 9 (2): 185-199.

Bae, J. and Tomizuka, M. (2012). A gait rehabilitation strategy inspired by an iterative learning algorithm. *Mechatronics*, 22 (2): 213-221.

Baharom, A. and Hashim, N. L. (2013). PID Controller Tuning by Differential Evolution Algorithm on EDM Servo Control System. *Applied Mechanics and Materials*, 3 (5): 2266-2270.

Balochian, S. (2013). Design of Combined Sliding Mode Controller Back Stepping Using Genetic Algorithm. *Journal of Engineering*, 2013 (1): 1-6.

Bhattacharya, S. K. (2009). *Control Systems Engineering*. 2nd ed. Delhi, India: Pearson Education India.

Boutaghou, Z., Erdman, A. G. and Stolarski, H. K. (1992). Dynamics of Flexible Beams and Plates in Large Overall Motions. *Journal of Applied Mechanics*, 59 (4): 991-999.

Bristow, D. A., Tharayil, M. and Alleyne, A. G. (2006). A Survey of Iterative Learning Control. *Control Systems, IEEE*, 26 (3): 96-114.

Bu, X., Ye, L., Su, Z. and Wang, C. (2003). Active Control of a Flexible Smart Beam Using a System Identification Technique Based on ARMAX. *Smart Materials and Structures*, 12 (5): 845–850.

Canahuire, R. V. and Serpa, A. L. (2012). A Direct Minimization Method to Reduced Order H-Infinity Controller Design: A Genetic Algorithm Approach. *Symposium Series in Mechatronics*, 2 (1): 245-251.

Caruso, G., Galeani, S. and Menini, L. (2003). Active Vibration Control of an Elastic Plate Using Multiple Piezoelectric Sensors and Actuators. *Simulation Modelling Practice and Theory*, 11 (5-6): 403-419.

Chakraborty, U. K. (2008). *Advances in Differential Evolution*. Berlin Heidelberg: Springer Publishing Company, Incorporated.

Chen, C. K. and Zeng, W. C. (2003). The Iterative Learning Control for the Position Tracking of the Hydraulic Cylinder. *JSME International Journal Series C*, 46 (2): 720-726

Chen, W., Chen, Y.-Q. and Yeh, C.-P. (2012). Robust Iterative Learning Control via Continuous Sliding-mode Technique with Validation on an SRV02 Rotary Plant. *Mechatronics*, 22 (5): 588-593.

Chhabra, D., Chandna, P. and Bhushan, G. (2011). Design and Analysis of Smart structures for Active Vibration Control using Piezo-Crystals. *International Journal of Engineering and Technology*, 1 (3): 153-163.

Chhabra, D., Narwal, K. and Singh, P. (2012). Design and Analysis of Piezoelectric Smart Beam for Active Vibration Control. *International Journal of Advancements in Research and Technology*, 1 (1): 1-5.

Christopher, F. (2007). *Handbook of Noise and Vibration Control*. Virginia: John Wiley & Sons Inc.

Clarke, D. W. (1996). Self-tuning Control. In Levine, W. S. (ed.) *The Control Handbook*, pp. 827-846. Boca Raton, FL: CRC/IEEE Press.

Coelho, L. D. S., Pessôa, M. W., Rodrigues Sumar, R. and Augusto, R. C. A. (2010). Model-free Adaptive Control Design using Evolutionary-neural Compensator. *Expert Systems with Applications*, 37 (1): 499-508.

Coelho, L. d. S. and Cunha, M. A. B. (2011). Adaptive Cascade Control of a Hydraulic Actuator with an Adaptive Dead-zone Compensation and Optimization Based on Evolutionary Algorithms. *Expert Systems with Applications*, 38 (10): 12262-12269.

Darus, I. Z. M. (2004). *Soft Computing Adaptive Active Vibration Control of Flexible Structures*. UK: University of Sheffield, Department of Automatic Control and Systems Engineering.

Darus, I. Z. M. and Tokhi, M. O. (2005). Soft Computing-based Active Vibration Vontrol of a Flexible Structure. *Journal of Engineering Application of Artificial Intelligence*, 18: 95-114.

Darus, I. Z. M. and Al-Khafaji, A. A. M. (2012). Non-parametric Modelling of a Rectangular Flexible Plate Structure. *Engineering Applications of Artificial Intelligence*, 25 (1): 94-106.

Darwin, C. (1859). *The Origin of Spicies*. London: John Murray.

de Moura Oliveira, P. B. (2005). Modern Heuristics Review for PID Control Optimization: a Teaching Experiment. *Proceeding of International Conference on Control and Automation*, Budapest, Hungary. 26-29 June 2005. 828-833

Demirci, M. U. and Nguyen, C. T. C. (2003). Higher-mode Free-free Beam Micromechanical Resonators. *International Frequency Control Symposium and PDA Exhibition Jointly with the 17th European Frequency and Time Forum*, Tampa, Florida, USA. 4-8 May 2003. 810-818.

Diaz, C. G. and Gardonio, P. (2007). Feedback Control Laws for Proof-Mass Electrodynamic Actuators. *Smart Materials and Structures*, 16 (5): 1766.

Dobrzanski, L. A., Honysz, R. and Fassois, S. (2006). On the Identification of Composite Beam Dynamics Based Upon Experimental Data. *Journal of Achievements in Materials and Manufacturing Engineering*, 16 (1): 114-123.

E. Pitowarno and M. Mailah. (2007). Control of Mobile Manipulator using Resolved Acceleration with Iterative-Learning-Proportional-Integral Active Force Control. *International Review of Mechanical Engineering*, 1 (5): 549-558.

Eski, İ. and Yildirim, Ş. (2009). Vibration Control of Vehicle Active Suspension System Using a New Robust Neural Network Control System. *Simulation Modelling Practice and Theory*, 17 (5): 778-793.

Ezhilarasi, D., Umapathy, M. and Bandyopadhyay, B. (2006). Design and Experimental Evaluation of Piecewise Output Feedback Control for Structural Vibration Suppression. *Smart Materials and Structures*, 15 (6): 1927.

Falangas, E. T., Dworak, J. and Koshigoe, S. (1994). Controlling Plate Vibrations Using Piezoelectric Actuators. *Control Systems, IEEE*, 14 (4): 34-41.

Fei, J., Fang, Y. and Yan, C. (2010). The Comparative Study of Vibration Control of Flexible Structure Using Smart Materials. *Mathematical Problems in Engineering*, 2010 (1): 1-13.

Fisher, R. A. (1930). *The Genetical Theory of Natural Selection*. Oxford: Clarendon Press.

Fleming, P. J. and Purshouse, R. C. (2002). Evolutionary Algorithms in Control Systems Engineering: a Survey. *Control Engineering Practice*, 10 (11): 1223-1241.

G. H. Cohen and G. A. Coon. (1953). Theoretical Consideration of Retarded Control. *Trans. ASME*, 75: 827–834.

Gani, A., Salami, M. J. E. and Khan, M. R. (2006). Compensated Inverse PID Controller for Active Vibration Control with Piezoelectric Patches: Modeling, Simulation and Implementation. *IIUM Engineering Journal*, 7 (2): 43-58.

Gen, M. and Cheng, R. (1999). *Genetic Algorithms and Engineering Optimization*, vol. 7. United States of America: Wiley-Interscience.

Goldberg, D. E. (1989). *Genetic Algorithms in Search, Optimization, and Machine Learning*: Addison-Wesley Publishing Co., Inc.

Guessas, L. and Benmahammed, K. (2011). Adaptive Backstepping and PID Optimised by Genetic Algorithm in Control of Chaotic. *International Journal of Innovative Computing, Information and Control*, 7 (9): 5299-5312.

Hashim, S. Z. M., Tokhi, M. O. and Darus, I. Z. M. (2006). Active Vibration Control of Flexible Structures Using Genetic Optimisation. *Journal of Low Frequency Noise, Vibration and Active Control*, 25 (3): 195-207.

Hassan, M. F., Mailah, M., Junid, R. and Alang, N. A. (2010). Vibration Suppression of a Handheld Tool Using Intelligent Active Force Control. *Proceedings of the World Congress on Engineering*, London, UK. June 30 - July 2. London, UK.

Hassan, M. K., Azubir, N. A. M., Nizam, H. M. I., Toha, S. F. and Ibrahim, B. S. K. K. (2012). Optimal Design of Electric Power Assisted Steering System (EPAS) Using GA-PID Method. *Procedia Engineering*, 41: 614-621.

Holland, J. H. (1975). *Adaptation in Natural and Artificial Systems*. Ann Arbor, MI: The University of Michigan Press.

Hossain, M. A., Tokhi, M. O., Chipperfield, A. J., Baxter, M. J., Fonseca, C. M. and Dakev, N. V. (1995). Adaptive Active Vibration Control Using Genetic Algorithms. *Genetic Algorithms in Engineering Systems: Innovations and Applications, 1995. GALESIA. First International Conference on (Conf. Publ. No. 414)*. 12-14 Sep 1995. 175-180.

Hossain, M. A. and Tokhi, M. O. (2006). Real-time Design Constraints in Implementing Active Vibration Control Algorithms. *International Journal of Automation and Computing*, 3 (3): 252-262.

Huang, Z. and Cheng, H. X. (2011). Implementing Iterative Learning Control to Reduce Torque Ripple of Permanent Magnet Synchronous Machine. *Advanced Materials Research*, 301 (1): 1676-1681.

Hyo-Sung, A., YangQuan, C. and Moore, K. L. (2007). Iterative Learning Control: Brief Survey and Categorization. *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on*, 37 (6): 1099-1121.

Instruments, N. (2008). *High-Speed M Series Multifunction Data Acquisition, NI PCIe-6259* Austin, Texas, USA.

Isabelle, B., Laurent, G. and Shahram, N. (2010). Optimal piezoelectric actuator and sensor location for active vibration control, using genetic algorithm. *Journal of Sound and Vibration*, 329 (10): 1615-1635.

Jain, T. and Nigam, M. J. (2008). Optimisation of PD-PI Controller Using Swarm Intelligence. *Journal of Theoretical and Applied Information Technology*, 4 (11): 1013-1018.

Jinghui, Z., Xiaomin, H., Min, G. and Jun, Z. (2005). Comparison of Performance between Different Selection Strategies on Simple Genetic Algorithms. *Proceedings of the International Conference on Computational Intelligence for Modelling, Control and Automation and International Conference on Intelligent Agents, Web Technologies and Internet Commerce Vol-2 (CIMCA-IAWTIC'05)*, Vienna, Austria 28-30 Nov. 2005. 1115-1121.

Jnifene, A. and Andrews, W. (2004). Fuzzy Logic Control of the End-Point Vibration in an Experimental Flexible Beam. *Journal of Vibration and Control*, 10 (4): 493-506.

Julai, S. and Tokhi, M. O. (2010a). SISO and SIMO Active Vibration Control of a Flexible Plate Structure using Real-coded Genetic Algorithm. *IEEE 9th International Conference on Cybernetic Intelligent Systems (CIS)*, Reading, UK. 1-2 Sept. 2010. 1-6.

Julai, S. and Tokhi, M. O. (2010b). Vibration Suppression of Flexible Plate Structures Using Swarm and Genetic Optimization Techniques. *Journal of Low Frequency Noise Vibration and Active Control*, 29 (4): 293-318.

Kanthalashmi, S. (2010). Genetic Algorithm Based Self Tuning Regulator. *International Journal of Engineering Science and Technology*, 2 (12): 7719-7728.

Karaboga, D. and Okdem, S. (2004). A Simple and Global Optimization Algorithm for Engineering Problems: Differential Evolution Algorithm. *Turkey Jurnal Electrical Engineering*, 12 (1): 53-60.

Karaboga, N. (2005). Digital IIR Filter Design Using Differential Evolution Algorithm. *EURASIP Journal on Applied Signal Processing*, 2005 (8): 1269-1276.

Kawamura, S., Miyazaki, F. and Arimoto, S. (1985). Applications of Learning Method for Dynamic Control of Robot Manipulators. *IEEE Conference on Decision and Control*, Bonaventure Intercontinental. Fort Lauderdale, Florida. 11-13 Dec. 1985. 1381-1386.

Khot, S. M., Yelve, N. P., Tomar, R., Desai, S. and Vittal, S. (2012). Active Vibration Control of Cantilever Beam by Using PID Based Output Feedback Controller. *Journal of Vibration and Control*, 18 (3): 366-372.

Kim, J. S., Kim, J. H., Park, J. M., Park, S. M., Choe, M. Y. and Heo, H. (2008). Auto Tuning PID Controller Based on Improved Genetic Algorithm for Reverse Osmosis Plant. *International Journal of Intelligent Systems and Technologies*, 3 (4): 232-237.

Kircali, Ö. F., Yaman, Y., Nalbantoğlu, V. and Şahin, M. (2008). Active Vibration Control of a Smart Beam by Using a Spatial Approach. *New Developments in Robotics, Automation and Control, ed. Aleksandar Lazinica, I-Tech Education and Publishing*: 377-410.

Kumar, K. R. and Narayanan, S. (2008). Active Vibration Control of Beams with Optimal Placement of Piezoelectric Sensor/Actuator Pairs. *Smart Materials and Structures*, 17 (5).

Kumar, R. and Singh, S. P. (2006). Adaptive Hybrid Control of Smart Structures Subjected to Multiple Disturbances. *Smart Materials and Structures*, 15 (5): 1345.

Kumar, R., Singh, S. P. and Chandrawat, H. N. (2006). Adaptive Vibration Control of Smart Structures: A Comparative Study. *Smart Materials and Structures*, 15 (5): 1358.

Kumar, R. and Khan, M. (2007). Pole-placement Techniques for Active Vibration Control of Smart Structures: A Feasibility Study. *Journal of Vibration and Acoustics*, 125 (5): 601-615.

Kunihiko, N., Kouhei, O., Hiroshi, K. and Tetsuhiko, Y. (2008). Vibration Control of Load for Rotary Crane System Using Neural Network with GA-Based Training. *Artificial Life and Robotics*, 13 (1): 98-101.

Lee, K. Y. and El-Sharkawi, M. A. (2008). *Modern Heuristic Optimization Techniques: Theory and Applications to Power Systems*, vol. 39: Wiley-IEEE press.

Li, J., Shang, C. and Zou, M. (2007). Parameter Optimization of Linear Quadratic Controller Based on Genetic Algorithm. *Tsinghua Science and Amp Technology*, 12 (0): 208-211.

Liang, W., Huai-hai, C. and Xu-dong, H. (2011). Active H∞ Control of the Vibration of an Axially Moving Cantilever Beam by Magnetic Force. *Mechanical Systems and Signal Processing*, 25 (8): 2863-2878.

Lin, W.-Y., Lee, W.-Y. and Hong, T.-P. (2003). Adapting Crossover and Mutation Rates in Genetic Algorithms. *Journal of Information Science and Engineering*, 19 (5): 889-904.

Lueg, P. (1936). *Process of Silencing Sound Oscillations*. U.S. Patent 2 043 416.

Madkour, A., Hossain, M. A., Dahal, K. P. and Yu, H. (2007). Intelligent Learning Algorithms for Active Vibration Control. *IEEE Transactions on Systems, Man, And Cybernetics— Part C: Applications And Reviews*, 37 (1): 1022-1033.

Mahmoodi, S. N., Aagaah, M. R. and Ahmadian, M. (2009). Active Vibration Control of Aerospace Structures Using a Modified Positive Position Feedback Method. *Proceedings of the 2009 conference on American Control Conference*, St. Louis, Missouri, USA. 10-12 June 2009: IEEE Press. 4115-4120.

Mahmoodi, S. N. and Ahmadian, M. (2009). Active Vibration Control with Modified Positive Position Feedback. *Journal of Dynamic Systems, Measurement, and Control*, 131 (4): 1-8.

Mahmoodi, S. N., Ahmadian, M. and Inman, D. J. (2010). Adaptive Modified Positive Position Feedback for Active Vibration Control of Structures. *Journal of Intelligent Material Systems and Structures*, 21 (6): 571-580.

Mailah, M. (1998). *Intelligent Active Force Control of A Rigid Robot Arm Using Neural Network and Iterative Learning Algorithms*. PhD Thesis, UK: University of Dundee.

Mailah, M. and Shiung, J. C. W. (2002). Control of a Robot Arm Using Iterative Learning Algorithm with a Stopping Criterion *Jurnal Teknologi,Universiti Teknologi Malaysia* 37(A): 55-72.

Manning, W. J., Plummer, A. R. and Levesley, M. C. (2000). Vibration Control of a Flexible Beam with Integrated Actuators and Sensors. *Smart Materials and Structures*, 9 (6): 932-939.

Marinaki, M., Marinakis, Y. and Stavroulakis, G. E. (2010). Fuzzy Control Optimized by PSO for Vibration Suppression of Beams. *Control Engineering Practice*, 18 (6): 618-629.

Marinaki, M., Marinakis, Y. and Stavroulakis, G. E. (2011). Vibration Control of Beams with Piezoelectric Sensors and Actuators using Particle Swarm Optimization. *Expert Systems with Applications*, 38 (6): 6872-6883.

Mat Darus, I. Z. and Tokhi, M. O. (2004). Genetic Algorithms Based Adaptive Active Vibration Control of a Flexible Structure. *Systems Science*, 29 (3): 65-79.

Ming-Chang, P. (2011). Closed-Loop Input Shaping Control of Vibration in Flexible Structures Using Discrete-Time Sliding Mode. *International Journal of Robust and Nonlinear Control*, 21 (7): 725-737.

Mitchell, A. R. and Griffiths, D. F. (1980). *The Finite Difference Method in Partial Differential Equations*. Chichester, Sussex, England and New York: Wiley-Interscience.

Mohamad, M., Tokhi, M. O. and Latiff, I. A. (2010). Particle Swarm Optimisation with Dynamic Spread Factor with Application to Modelling of a Flexible Beam Structure. *IEEE 9th International Conference on Cybernetic Intelligent Systems (CIS)*, Reading, UK. 1-2 Sept. 2010. 1-6.

Moore, K. L. (1993). *Iterative Learning Control For Deterministic Systems*: Springer-Verlag London Limited.

Narayanan, S. and Balamurugan, V. (2003). Finite Element Modelling of Piezolaminated Smart Structures for Active Vibration Control with Distributed Sensors and Actuators. *Journal of Sound and Vibration*, 262 (3): 529-562.

Oh, S.-K., Kim, W.-D. and Pedrycz, W. (2012). Design of Optimized Cascade Fuzzy Controller Based on Differential Evolution: Simulation Studies and Practical Insights. *Engineering Applications of Artificial Intelligence*, 25 (3): 520-532.

Oliveira, P., Sequeira, J. and Sentieiro, J. (1991). *Selection of Controller Parameters Using Genetic Algorithms*. Dordrecht, Netherlands Kluwer Academic Publishers.

Pan, X., Moore, S. and Forrest, J. A. (2011). Design and Evaluation of a Pole-placement Controller for Controlling Vibration of Structures. *Proceedings of Acoustics*, Gold Coast, Australia. 2-4 November. 1-8.

Panasonic Electric Works Europe AG. (2005). *Micro Laser Displacement Sensor*. Holzkirchen.

Panda, S. (2009). Differential Evolutionary Algorithm for TCSC-based Controller Design. *Simulation Modelling Practice and Theory*, 17 (10): 1618-1634.

Perdikaris, G. A. (1991). *Computer Controlled Systems: Theory and Applications*. Dordrecht: Kluwer Academic.

Physik Instrumente (PI) GmbH & Co. (2012a). *P-876 DuraAct Patch Transducer*. Karlsruhe, Germany.

Physik Instrumente (PI) GmbH & Co. (2012b). *E-835 DuraAct™ Piezo Driver Module* Karlsruhe, Germany.

Pishkenari, H. N., Mahboobi, S. H. and Alasty, A. (2011). Optimum synthesis of fuzzy logic controller for trajectory tracking by differential evolution. *Scientia Iranica*, 18 (2): 261-267.

Pishkenaria, H. N., Mahboobib, S. H. and Alastya, A. (2011). Optimum Synthesis of Fuzzy Logic Controller for Trajectory Tracking by Differential Evolution. *Scientia Iranica*, 18 (2): 261-267.

Pitowarno, E. and Mailah, M. (2007). Control of Mobile Manipulator using Resolved Acceleration with Iterative-Learning-Proportional-Integral Active Force Control. *International Review of Mechanical Engineering*, 1 (5): 549-558.

Porter, B. and Jones, A. H. (1992). Genetic Tuning of Digital PID Controllers. *Electronics Letters*, 28 (9): 843-844.

Preumont, A. (2011a). *Electromagnetic and Piezoelectric Transducers Vibration Control of Active Structures*, vol. 179: Springer Netherlands. 41-59 pp.

Preumont, A. (2011b). *Vibration Control of Active Structures*, vol. 179: Springer Science+ Business Media.

Proakis, J. G. and Manolakis, D. G. (1996). *Digital Signal Processing: Principles, Algorithms and Applications* New Jersey: Prentice-Hall.

Qiu, Z. C., Shi, M. L., Wang, B. and Xie, Z. W. (2012). Genetic Algorithm Based Active Vibration Control for a Moving Flexible Smart Beam Driven by a Pneumatic Rod Cylinder. *Journal of Sound and Vibration*, 331 (10): 2233-2256.

Rahman, T. A. Z. and Darus, I. Z. M. (2012). Active vibration control using pole-placement method of a flexible plate structure optimised by genetic algorithm. *Control, Systems & Industrial Informatics (ICCSII), 2012 IEEE Conference on*. 23-26 Sept. 2012. 92-97.

Reeves, C. R. (1995). *Modern Heuristic Techniques for Combinatorial Problems*. London: McGraw-Hill.

Roy, T. and Chakraborty, D. (2009). Optimal Vibration Control of Smart Fiber Reinforced Composite Shell Structures using Improved Genetic Algorithm. *Journal of Sound and Vibration*, 319 (1-2): 15-40.

Ruijun, D. (2009). Differential Evolution Versus Particle Swarm Optimization for PID Controller Design. *Fifth International Conference on Natural Computation, ICNC '09.* , Tianjin. 14-16 Aug. 2009. 236-240.

Salleh, S. M. and Tokhi, M. O. (2010). Self-Tuning AIS-Based Active Vibration Control of a Thin Plate. *Cybernetic Intelligent Systems (CIS), 2010 IEEE 9th International Conference on*. 1-2 Sept. 2010. 1-6.

Saravanakumar, G., Wahidhabanu, R. S. D. and George, V. I. (2006). Robustness and Performance of Modified Smith Predictors for Processes with Longer Dead-Times. *International Journal on Automatic Control and System Engineering*, 6 (3): 41-46.

Scott, R. G., Brown, M. D., and Levesley, M., . (2001). Pole-placement Control of a Smart Vibrating Beam. *Proceedings of the 8th International Congress on Sound and Vibration*, Hong Kong. 387-390.

Sethi, V. and Song, G. (2006a). Pole-Placement Vibration Control of a Flexible Composite I-beam using Piezoceramic Sensors and Actuators. *Journal of Thermoplastic Composite Materials*, 19 (3): 293-307.

Shin, C., Hong, C. and Jeong, W. B. (2012). Active Vibration Control of Beam Structures Using Acceleration Feedback Control with Piezoceramic Actuators. *Journal of Sound and Vibration*, 331 (6): 1257-1269.

Slavov, T. and Roeva, O. (2012). Application of Genetic Algorithm to Tuning a PID Controller for Glucose Concentration Control. *WSEAS Transactions on Systems*, 11 (7).

Spearritt, D. J. and Ashokanathan, S. F. (1996). Torsional Vibration Control of A Flexible Using Laminated PVDF Actuators. *Journal of Sound and Vibration*, 193 (5): 941-956.

Storn, R. and Price, K. (1995). Differential Evolution – A Simple and Efficient Adaptive Scheme for Global Optimization Over Continuous Spaces. *Technical Report TR-95-012*: International Computer Science Institute.

Storn, R. (1996). On the Usage of Differential Evolution for Function Optimization. *Proceedings of the Fuzzy Information Processing Society*, Berkeley, CA, USA. 19-22 Jun 1996. 519-523.

Storn, R. and Price, K. (1997). Differential Evolution – A Simple and Efficient Heuristic for Global Optimization over Continuous Spaces. *Journal of Global Optimization*, 11 (4): 341–359.

Sung-Kwun, O., Han-Jong, J. and Witold, P. (2009). The Design of a Fuzzy Cascade Controller for Ball and Beam System: A Study in Optimization with the Use of Parallel Genetic Algorithms. *Engineering Applications of Artificial Intelligence*, 22 (2): 261-271.

Suzuki, Y. and Kagawa, Y. (2010). Active Vibration Control of a Flexible Cantilever Beam Using Shape Memory Alloy Actuators. *Smart Materials and Structures*, 19 (8): 1-9.

Tavakolpour, A. R., Mailah, M., Mat Darus, I. Z. and Tokhi, O. (2010a). Self-learning Active Vibration Control of a Flexible Plate Structure with Piezoelectric Actuator. *Simulation Modelling Practice and Theory*, 18 (5): 516-532.

Tavakolpour, A. R., Mat Darus, I. Z., Tokhi, O. and Mailah, M. (2010b). Genetic Algorithm-based Identification of Transfer Function Parameters for a Rectangular Flexible Plate System. *Engineering Applications of Artificial Intelligence*, 23 (8): 1388-1397.

Tayebi, A. and Islam, S. (2006). Adaptive Iterative Learning Control for Robot Manipulators: Experimental Results. *Control Engineering Practice*, 14 (7): 843-851.

Tehrani, M. G., Mottershead, J. E., Shenton, A. T. and Ram, Y. M. (2011). Robust Pole-placement in Structures by the Method of Receptances. *Mechanical Systems and Signal Processing*, 25 (1): 112-122.

Thomson, T. (1993). *Theory of Vibration with Applications*. 4 ed. London: Chapman and Hall.

Tijani, I. B., Akmeliawati, R., Muthalif, A. G. A. and Legowo, A. (2011). Optimization of PID Controller for Flexible Link System using a Pareto-based Multi-objective Differential Evolution. *4th International Conference On Mechatronics (ICOM)*, Kuala Lumpur, Malaysia. 17-19 May 2011. 1-6.

Timoshenko, S. P. (1953). *History of Strength of Materials*. New York: McGraw-Hill.

Tjahyadi, H., He, F. and Sammut, K. (2006). Multi-Mode Vibration Control of a Flexible Cantilever Beam using Adaptive Resonant Control. *Smart Materials and Structures*, 15 (2): 270.

Tokhi, M. and Hossain, M. A. (1994). Self-tuning Active Vibration Control in Flexible Beam Structures. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, 208 (4): 263-278.

Tokhi, M. O. and Leitch, R. R. (1992). *Active Noise Control*. Oxford, U.K.: Clarendon.

Tokhi, M. O. and Hossain, M. A. (1996). A Unified Adaptive Active Control Mechanism for Noise Cancellation and Vibration Suppression. *International Journal of Mechanical Systems and Signal Processing*, 10: 667-682.

Tripathi, P. K. and Gangadharan, K. V. (2012). Design and Implementation of Active Vibration Control in Smart Structures. *International Journal of Research and Reviews in Mechatronic Design and Simulation*, 2 (1): 92-98.

Van De Wijdeven, J. and Bosgra, O. (2007). Hankel Iterative Learning Control for Residual Vibration Suppression with MIMO Flexible Structure Experiments. *Proceedings of the 2007 American Control Conference Marriott Marquis Hotel*, Times Square New York City, USA. July 11 - 13. 120 -125.

Vasques, C. M. A. and Dias, R. J. (2006). Active Vibration Control of Smart Piezoelectric Beams: Comparison of Classical and Optimal Feedback Control Strategies. *Computers & Structures*, 84 (22–23): 1402-1414.

Virk, G. S. and Al-Dmour, A. S. (1999). Real-Time Vibration Suppression in a Flexible Cantilever Rig. *Microprocessors and Microsystems*, 23 (6): 365-384.

Wakasa, Y., Tanaka, K., Akashi, T. and Nishimura, Y. (2010). PSO Based Simulteneous Tuning Method for PID Controllers and Dead-Zone Compensator and its Application to Ultrasonic Motors. *International Journal of Innovative Computing, Information and Control*, 6 (10): 4593-4604.

Wali, W. A., Hassan, K. H., Cullen, J. D., Shaw, A. and Al-Shamma'a, A. I. (2013). Real-time Monitoring and Intelligent Control for Novel Advanced Microwave Biodiesel Reactor. *Measurement*, 46 (1): 823-839.

Wall, J. (2003). Dynamics Study of an Automobile Exhaust System. *Licentiate Dissertation Series* (2003): 08.

Wang, C. and Lai, J. C. S. (2000). Modelling the Vibration Behaviour of Infinite Structures by FEM. *Journal of Sound and Vibration*, 229 (3): 453-466.

Wang, K., Xiong, S. and Zhang, J. (2011b). Active Vibration Control of a Flexible Cantilever Beam Using Piezoelectric Actuators. *Energy Procedia*, 13: 4367-4374.

Wang, Y., Gao, F. and Doyle Iii, F. J. (2009). Survey on Iterative Learning Control, Repetitive Control, and Run-to-run Control. *Journal of Process Control*, 19 (10): 1589-1600.

Weaver, W., Timoshenko, S. P. and Young, D. H. (1990). *Vibration Problems in Engineering*. 5 ed. New York: Wiley.

Wellstead, P. E. and Zarrop, M. B. (1991). *Self-Tuning Systems: Control and Signal Processing*, vol. 1. New York, NY, USA: John Wiley & Sons, Inc. .

Wu, D. F., Huang, L., Su, F., Liu, C. X., Yang, H. Y. and Liu, A. C. (2011). Realization of Active Vibration Control on Piezoelectric Intelligent Flexible Beam. *Advanced Materials Research* 383 - 390: 5580-5585.

Yang, J. and Chen, G. (2011). Adaptive Iterative Learning Control for Vibration of Flexural Rectangular Plate. *Mechanika*, 17 (5): 485-491.

Yin, F., Wang, J. and Guo, C. (2004). *Design of PID Controllers Using Genetic Algorithms Approach for Low Damping Slow Response Plants*. Advances in Neural Networks. Berlin Heidelberg: Springer-Verlag 219-220 pp.

You, B., Kim, M., Lee, D., Lee, J. and Lee, J. S. (2011). Iterative Learning Control of Molten Steel Level in a Continuous Casting Process. *Control Engineering Practice*, 19 (3): 234-242.

Young, P. C. and Jakeman, A. J. (1980). Refined Variable Instrumental Methods of Time Series Analysis. *International Journal of Control*, 31: 741-764.

Yousefi, H., Hirvonen, M., Handroos, H. and Soleymani, A. (2008). Application of Neural Network in Suppressing Mechanical Vibration of a Permanent Magnet Linear Motor. *Control Engineering Practice*, 16 (7): 787-797.

Youxin, L. and Xiaoyi, C. (2010). Tuning PID Control Parameters on Hydraulic Servo Control System Based on Differential Evolution Algorithm. *Proceedings of the Second International Conference on Advanced Computer Control (ICACC)*, Shenyang. 27-29 March 2010. 348-351.

Zafer, B. (2004). A New PID Tuning Technique Using Differential Evolution for Unstable and Integrating Processes with Time Delay. In Lecture Notes in Computer Science, vol. 3316 *Neural Information Processing*, pp. 254-260. Berlin Heidelberg: Springer

Zain, B. A. M., Tokhi, M. O. and Toha, S. F. (2009). PID-based Control of a Single-Link Flexible Manipulator in Vertical Motion with Genetic Optimisation. *Third UKSim European Symposium on Computer Modeling and Simulation*, Athens, Greece 25-27 Nov. 2009 355-360.

Zain, M. Z. M. and Tokhi, M. O. (2006). Hybrid Learning Control Schemes with Input Shaping of a Flexible Manipulator System. *Mechatronics* 12 (1): 209-219.

Zhang, J., Guo, X., He, L. and Gao, R. (2011). Study of Fuzzy Control for Intelligent Cantilever Beam Based on Genetic Algorithm. *Advanced Materials Research*, 204 (1): 25-30.

Zhang, T. and Li, H. G. (2012). Adaptive Pole-placement Control for Vibration Control of a Smart Cantilevered Beam in Thermal Environment. *Journal of Vibration and Control*, 18 (12): 1-11.

Zhi-cheng, Q., Jian-da, H., Xian-min, Z., Yue-chao, W. and Zhen-wei, W. (2009). Active Vibration Control of a Flexible Beam Using a Non-Collocated Acceleration Sensor and Piezoelectric Patch Actuator. *Journal of Sound and Vibration*, 326 (3-5): 438-455.

Ziegler, J. G. and Nichols, N. B. (1942). Optimum Settings for Automatic Controllers. *Trans. ASME*, 64 (8): 759–768.

Zilletti, M., Elliott, S. J. and Gardonio, P. (2010). Self-tuning Control Systems of Decentralised Velocity Feedback. *Journal of Sound and Vibration*, 329 (14): 2738-2750.