

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  
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*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 berkadar (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.

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## 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 parameter gain
$k_p$	-	Proportional gain
$L$	-	Length of the beam
$m$	-	Mass
$m_j$	-	Number of bits
$\mu$	-	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
$\Delta t$	-	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
$\Delta x$	-	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
$\lambda_l, \lambda_l^*$	-	$l$ -th discrete complex conjugate pair
$\rho$	-	Density
$\Phi$	-	Proportional learning parameter
$\beta_n$	-	Eigenvalue
$\zeta_l$	-	Damping ratio
$\omega$	-	Frequency (rad/s)
$\omega_{nl}$	-	$l$ -th natural frequency

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## **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**

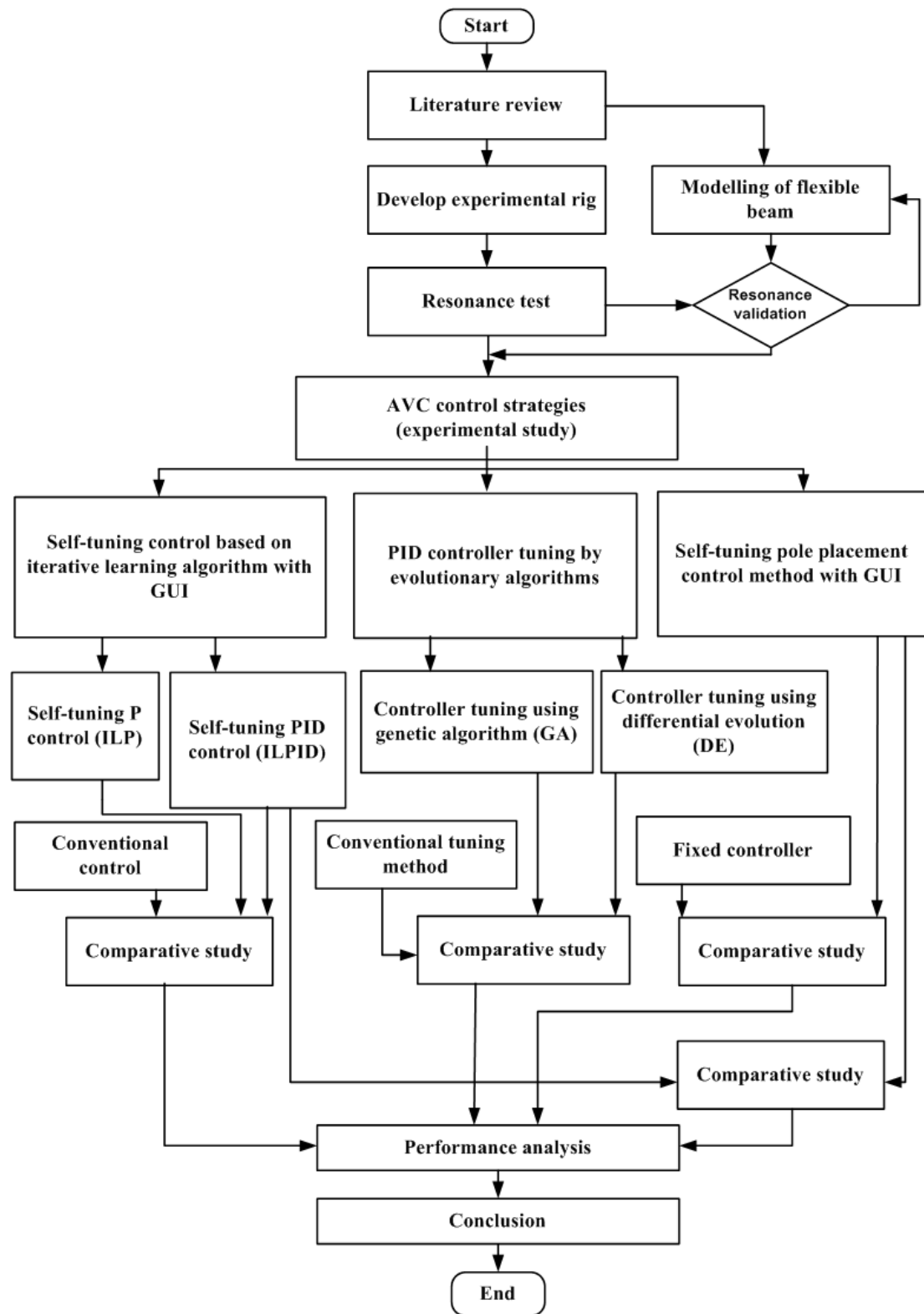
After literature review has been carried out, the simulation model of the beam is developed using finite difference method. The modeling is done using suitable programming environment. The deflection of the beam can be observed dynamically at a finite duration of time. The simulated model is validated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

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