# ACTIVE VIBRATION CONTROL OF FLEXIBLE BEAM INCORPORATING RECURSIVE LEAST SQUARE AND NEURAL NETWORK ALGORITHMS

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*In the name of ALLAH, the Most Gracious and the Most Merciful*

*To my dearest husband Muhammad ‘Aizat Bin Rahman, who are always by my side for all this time, through hardships and obstacles, for your support and encouragements that made it possible for me to complete my study. Deep in my heart, you are the one that I will always in love.*

*To my sons Muhammad Rayyan Alfateh Bin Muhammad ‘Aizat and Muhammad Arslan Wafiy Aladl Bin Muhammad ‘Aizat. Both of you are my soul and have completed my life as an ibu.*

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## ABSTRACT

In recent years, active vibration control (AVC) has emerged as an important area of scientific study especially for vibration suppression of flexible structures. Flexible structures offer great advantages in contrast to the conventional structures, but necessary action must be taken for cancelling the unwanted vibration. In this research, a simulation algorithm representing flexible beam with specific conditions was derived from Euler Bernoulli beam theory. The proposed finite difference (FD) algorithm was developed in such way that it allows the disturbance excitation at various points. The predicted resonance frequencies were recorded and validated with theoretical and experimental values. Subsequently, flexible beam test rig was developed for collecting data to be used in system identification (SI) and controller development. The experimental rig was also utilised for implementation and validation of controllers. In this research, parametric and nonparametric SI approaches were used for characterising the dynamic behaviour of a lightweight flexible beam using input-output data collected experimentally. Traditional recursive least square (RLS) method and several artificial neural network (ANN) architectures were utilised in emulating this highly nonlinear dynamic system here. Once the model of the system was obtained, it was validated through a number of validation tests and compared in terms of their performance in representing a real beam. Next, the development of several conventional and intelligent control schemes with collocated and non-collocated actuator sensor configuration for flexible beam vibration attenuation was carried out. The investigation involves design of conventional proportional-integral-derivative (PID) based, Inverse recursive least square active vibration control (RLS-AVC), Inverse neuro active vibration control (Neuro-AVC), Inverse RLS-AVC with gain and Inverse Neuro-AVC with gain controllers. All the developed controllers were tested, verified and validated experimentally. A comprehensive comparative performance to highlight the advantages and drawbacks of each technique was investigated analytically and experimentally. Experimental results obtained revealed the superiority of Inverse RLS-AVC with gain controller over conventional method in reducing the crucial modes of vibration of flexible beam structure. Vibration attenuation achieved using proportional (P), proportional-integral (PI), Inverse RLS-AVC, Inverse Neuro-AVC, Inverse RLS-AVC with gain and Inverse Neuro-AVC with gain control strategies are 9.840 dB, 6.840 dB, 9.380 dB, 8.590 dB, 17.240 dB and 5.770 dB, respectively.

# ABSTRAK

Beberapa tahun kebelakangan ini, kawalan getaran aktif (AVC) muncul sebagai bidang penting di dalam kajian saintifik terutamanya bagi pengurangan getaran struktur fleksibel. Struktur fleksibel menawarkan banyak kelebihan berbanding dengan struktur konvensional, tetapi langkah pencegahan perlu diambil untuk mengurangkan getaran yang tidak diingini. Dalam kajian ini, algoritma simulasi yang mewakili model rasuk fleksibel dengan syarat-syarat tertentu diperolehi daripada teori rasuk Euler Bernoulli. Cadangan algoritma perbezaan terhingga (FD) dibangunkan dengan cara ia membolehkan pengujaan gangguan dilakukan di beberapa tempat yang berbeza. Ramalan frekuensi resonans direkodkan dan disahkan dengan nilai yang diperolehi dari teori dan eksperimen. Selepas itu, pelantar ujian rasuk fleksibel dibangunkan untuk mengumpul data yang akan digunakan di dalam pengenalpastian sistem dan pembangunan pengawal. Pelantar ujian rasuk fleksibel juga akan digunakan di dalam uji kaji pelaksanaan dan pengesahan pengawal-pengawal yang telah dicadangkan. Dalam kajian ini, pendekatan identifikasi sistem (SI) parametrik dan bukan parametrik digunakan untuk mencirikan kelakuan dinamik masukan-keluaran menggunakan data masuk-keluar yang diperolehi melalui ujikaji. Kaedah tradisional kuasa dua terkecil recursive (RLS) dan beberapa senibina neural network buatan (ANN) digunakan dalam mewakili sistem dinamik yang sangat tidak linear ini. Apabila model sistem diperolehi, ia disahkan melalui beberapa ujian pengesahan dan dibandingkan dari segi prestasi model-model tersebut dalam mewakili rasuk pelantar yang sebenar. Seterusnya, pembangunan beberapa skim kawalan konvensional dan pintar dengan konfigurasi penderia-penggerak di satu titik operasi yang sama dan berlainan bagi pengecilan getaran rasuk fleksibel dijalankan. Penyiasatan ini melibatkan reka bentuk pengawal konvensional terbitan-kamiran-berkadaran (PID), Songsangan kuasa dua terkecil recursive bagi kawalan getaran aktif (RLS-AVC), Songsangan neuro bagi kawalan getaran aktif (Neuro-AVC), Songsangan RLS-AVC bersama gandaan dan Songsangan Neuro-AVC bersama gandaan. Semua pengawal-pengawal yang dibangunkan diuji dan disahkan melalui ujikaji yang dijalankan. Perbandingan secara menyeluruh untuk menonjolkan kelebihan dan kelemahan setiap teknik disiasat secara analisis dan ujikaji. Keputusan eksperimen yang diperolehi mendedahkan keunggulan pengawal Songsangan RLS-AVC bersama gandaan berbanding kaedah konvensional mengurangkan mod penting getaran struktur rasuk fleksibel. Jumlah pengurangan getaran yang diperoleh bagi pengawal terbitan (P), terbitan-kamiran (PI), Songsangan RLS-AVC, Songsangan Neuro-AVC, Songsangan RLS-AVC bersama gandaan dan Songsangan Neuro-AVC bersama gandaan adalah 9.840 dB, 6.840 dB, 9.380 dB, 8.590 dB, 17.240 dB and 5.770 dB.

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| ANC | - | Active noise control |
| ANFIS | - | Adaptive neuro-fuzzy inference system |
| ANN | - | Artificial neural network |
| AR | - | Autoregressive |
| ARMA | - | Autoregressive moving average |
| ARMAX | - | Autoregressive moving average moving average with exogenous inputs |
| AVC | - | Active vibration control |
| BE | - | Bias error |
| D | - | Derivative |
| DAQ | - | Data acquisition |
| CGC | - | Constant gain controller |
| DFC | - | Digital filter controller |
| FD | - | Finite difference |
| FE | - | Finite element |
| FFT | | Fast fourier transform |
| FTDNN | - | Focused time delay neural network |
| FV | - | Finite volume |
| GA | - | Genetic algorithm |
| GRNN | - | General regression neural network |
| I | - | Integral |
| ILA | - | Iterative learning algorithm |
| IV | - | Instrumental variables |
| I/O | - | Input/output |
| LMS | - | Least mean squares |
| LQG | - | Linear quadratic gaussian |

| | | |
|---|---|---|
| MIMO | - | Multiple input multiple output |
| MLP | - | Multi layered perceptron |
| MSE | - | Mean squared error |
| NARX | - | Nonlinear autoregressive with exogenous inputs |
| NARMAX | - | Nonlinear autoregressive moving average with exogenous inputs |
| Neuro-AVC | - | Neuro active vibration control |
| NN | - | Neural network |
| OSA | - | One step ahead |
| P | - | Proportional |
| PC | - | Personal computer |
| PD | - | Proportional-derivative |
| PDE | - | Partial differential equation |
| PEM | - | Prediction error method |
| PI | - | Proportional-integral |
| PID | - | Proportional-integral-derivative |
| PPF | - | Positive position feedback |
| PSO | - | Particle swarm optimization |
| PZT | - | Lead zirconate titanate |
| P-ILA | - | P with iterative learning algorithm |
| PID-ILA | - | PID with iterative learning algorithm |
| RBF | - | Radial basis function |
| RCGA | - | Recessive trait crossover genetic algorithm |
| RLS | - | Recursive least square |
| RLS-AVC | - | Recursive least square active vibration control |
| RMSE | - | Root mean squared error |
| SI | - | System identification |
| SIMO | - | Single input multiple output |
| SISO | - | Single input single output |
| SRF | - | Strain rate feedback |
| ZV | - | Two impulse sequence |
| ZVDD | - | Four impulse sequence |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $a$ | - | output of the neuron |
| $A$ | - | cross section area |
| $b$ | - | width (cross section of the cantilever beam) |
| $c_i$ | - | centre of each neuron |
| $C$ | - | transfer characteristic of controller |
| $C_n$ | - | tangent sigmoid neurons in its hidden (recurrent) layer |
| $d$ | - | distance between primary source and secondary source |
| $e(\tau)$ | - | impulse function |
| $e(t)$ | - | prediction error at time $t$ |
| $e(t,\alpha)$ | - | objective error function |
| $E$ | - | transfer function through distance $r_e$ |
| $E_M$ | - | Young's Modulus |
| $f_{nf}$ | - | natural frequency in Hz |
| $f(.)$ | - | nonlinear function |
| $F_A$ | - | force generated by actuator |
| $F_D$ | - | disturbance force |
| $G$ | - | transfer function through distance $r_g$ |
| $G_A$ | - | gain for actuator |
| $G_C$ | - | gain for controller |
| $G_P$ | - | gain for plant |
| $G_S$ | - | gain for sensor |
| $h$ | - | height (cross section of the cantilever beam) |
| $H$ | - | transfer function through distance $r_h$ |
| $H_n$ | - | hidden neuron |
| $i$ | - | point on the beam |
| $I$ | - | moment of inertia |

| | | |
|---|---|---|
| $j$ | - | time step |
| $K_D$ | - | gain for D controller |
| $K_I$ | - | gain for I controller |
| $K_P$ | - | gain for P controller |
| $L$ | - | transfer characteristic of secondary source |
| $L_T$ | - | total length |
| $m$ | - | mass of the beam |
| $M$ | - | transfer characteristic of detector |
| $\mathrm{M}(\mathrm{L}_T, t)$ | - | bending moment of the beam |
| $n_u$ | - | maximum lags in the input |
| $n_y$ | - | maximum lags in the output |
| $N$ | - | data length |
| $N_F$ | - | filter coefficient |
| $Q_0$ | - | subsystem transfer function when the secondary source is off |
| $Q_0^{-1}$ | - | inverse of $Q_0$ |
| $Q_1$ | - | subsystem transfer function when the secondary source is on |
| $r_e$ | - | distance between primary source and detection sensor |
| $r_g$ | - | distance between primary source and observed signal |
| $r_h$ | - | distance between secondary source and observed signal |
| S | - | stiffness matrix |
| $t$ | - | time |
| $T_S$ | - | sampling time |
| $u$ | - | input to neuron |
| $u_w$ | - | weighted output of the neuron |
| $U_C$ | - | secondary signal |
| $U_D$ | - | primary signal |
| $U_M$ | - | detected signal |
| $U(t)$ | - | applied force at time $t$ |
| $U(x,t)$ | - | applied force at point $x$ time $t$ |
| $\mathrm{V}(\mathrm{L}_T, t)$ | - | shear force of the beam |
| $w$ | - | weight |
| $x$ | - | distance from the fixed end of a flexible beam |
| $y$ | - | output |

| | | |
|---|---|---|
| $y(n)$ | - | real output |
| $y(t)$ | - | output at time $t$ |
| $y(x,t)$ | - | beam's deflection at point $i$ at time step $j$ |
| $\hat{y}(n)$ | - | predicted output |
| $\hat{y}(t\|t-1;\alpha)$ | - | the prediction of $y(t)$ given the data up to and including $y(t-1)$ |
| $Y$ | - | observed signal |
| $Y_C$ | - | corresponding signal at observation point |
| $Y_D$ | - | corresponding signal at observation point |
| $Y(t)$ | - | desired output at time $t$ |
| $\hat{Y}(t)$ | - | predicted output at time $t$ |
| $z$ | - | unit delay |
| $\alpha_n$ | - | Characteristic associated with each mode shape |
| $\beta_n$ | - | Eigenvalue |
| $\frac{\partial\ (0,t)}{\partial}$ | - | Slope of the beam at point 0 at time step $j$ |
| $\varepsilon(t)$ | - | residual for one-step ahead prediction |
| $\rho$ | - | density |
| $\mu$ | - | beam constant |
| $\theta$ | - | bias |
| $\lambda$ | - | convergence requirement |
| $\lambda_{ff}$ | - | forgetting factor |
| $\phi_i$ | - | Gaussian activation functions |
| $\phi_{ue}(\tau)$ | - | cross correlation function between $u(t)$ and $\varepsilon(t)$, |
| $\omega_{nf}$ | - | natural frequency in rad/s |
| $\Delta t$ | - | sampling time |
| $\Delta x$ | - | sections of equal length |
| $\Sigma$ | - | total summation |

# LIST OF APPENDICES


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# CHAPTER 1

# INTRODUCTION

## 1.1 Research Background

The emergence of industrial needs in flexible beam structures are very rapid in the last two decades replacing the conventional rigid structures especially in mechanical, aerospace, civil and architectural systems (Su and Chesnik Carlos, 2011; Damanpack *et al*., 2013; Pai, 2013; Panferov *et al*., 2013). The advantages of highly flexible beams benefited in many applications such as flexible robotic arms, helicopter rotor blades, lightweight turbine machine rotor blades, slender space structures for buildings to name a few. Flexible structures used less material and are lighter in weight, thus reducing the overall cost, man power, wind resistance and energy requirement. Despite all the advantages associated with flexible structures, reducing structure's size has a major drawback of higher sensitivity to unwanted vibration. If the machinery is being affected by unwanted vibration, many processes which require precision cannot take place (Lyshevski, 2003; Tao *et al*., 2006; Zhi and Ru-fei, 2010; Jian and Bin, 2010).

Unwanted vibration is undeniably a limiting factor and undesired phenomenon in system. Vibration occurs by introducing an excitation force either intentionally or unintentionally. Some of the effects of this vibration are affecting the machine's efficiency, reduce overall performance and life span of the system. Without proper precautions, this vibration capable of damaging and destructing the whole system. Hence, it is required to find the best solutions to overcome this crucial problem. In order to suppress the unwanted vibration acting on flexible systems, there are various strategies and attempts have been introduced over the past few years. The cheapest and easiest method is to introduce passive control strategy on the desired system. Passive scheme consists of mounting passive material such as vibration dampers and dynamic absorbers on the system. Still, this attempt might not efficient enough if to be implemented on flexible structures. Some of the major disadvantages of passive means are ineffective to be utilised at low frequencies and the additional volume and mass is impractical when physical space and mass loading are critical criteria in a system (Tokhi and Hossain, 1996; Meurers *et al*., 2003; Jnifene, 2007).

Aside from passive control, another approach which has received remarkable research attention in the last decade is active control. Active control is proven to be more effective, reliable, and flexible where the actuator can be adjusted according to the characteristic of vibration during operation. With the help of active vibration control (AVC), a precision industrial process can be maintained on a platform essentially vibration free. AVC concept is very different with passive strategy. In AVC, it reduces the amplitude of structural vibration of a dynamical system by introducing a secondary source of vibration to the dynamical system. With the superposition of waves (cancellation source), the aim is to destructively interfere with the unwanted source and thus result in a reduction in the level of vibration at desired location(s) (Mat Darus and Tokhi, 2005). Besides, it is possible to control the unwanted vibrations with a broad band frequency through the AVC. As a result, AVC is an encouraging method to be used in the field of flexible structures. Other applications of AVC are aerospace equipment, semiconductor industry, ground transportation equipment, aerospace, architectural systems and many more (Hudson and Reynolds, 2012; Wang *et al*., 2015; Enriquez-Zarate *et al*., 2016; Prakash *et al*., 2016; Shukla and Ghodki, 2016).

Thus, in this research, an investigation of an AVC for optimum vibration reduction of flexible beam which subjected to a vibration excitation. For the development of an artificial neural network (ANN) controller algorithm on vibrating structure, flexible beam structure with fixed-free ends condition is considered in this study. In order to develop an effective control mechanism for vibration suppression control, an accurate dynamic model which represents flexible beam structure is needed. Motivated by the proven advantages of finite difference (FD) approach for numerical analysis of flexible structures, this method is employed in this study and used to solve the partial differential equation (PDE) characterising the dynamic behaviour of a flexible beam system in specific condition. Next, system identification (SI) using parametric and ANN nonparametric techniques which determine model that best describes input and output behaviour of a system are presented. The parametric model of the system is developed using recursive least square (RLS), while nonparametric models are identified using several types of ANN and classified according to their structures.

## 1.2 Problem Statement

Vibration suppression is a crucial problem which related to flexible structures especially in the area of robotics system, where flexible structures offer several advantages compared to rigid structures. However, one of the major drawback in dealing with this structures is they are highly sensitive to the effect of unwanted oscillation. To avoid this limiting factor which undeniably affecting the system's overall performance, the best precautions must be taken in order to solve this problem. Therefore, several control schemes which utilising AVC methods have been designed in order to eliminate the unwanted oscillation acting on the flexible structures.

Despite the fact that there are countless control strategies have been devised for AVC on flexible beam structures. Nonetheless, AVC is still an open area of research to be explored. Furthermore, flexible structures are known to possess many resonance modes and low frequency. Thus, vibration control of nodes become an important issue to be handled. With the invention of piezoelectric patch, the device has become one of popular tool to apply in the study of AVC area. These smart materials are generally small in size, consume low energy, offer fast response and can be integrated with the flexible structures. Taking advantage from the ability of piezoelectric patch to convert mechanical to electric energy and vice versa, this fact was used in this research as actuation strategy (acts as sensor or actuator), (Schoeftner *et al.*, 2015).

Hence, in this study, simulation and experimental study of PID based and Inverse AVC control schemes were conducted in order to find the best method able to damp the unwanted oscillation of the system. In the beginning, best model which represents the flexible beam was estimated using RLS and four types of ANN architectures. Then, PID based and Inverse AVC control schemes were developed offline to investigate the performance of each controller in attenuating the unwanted vibration acting on flexible beam. Finally, all these controllers were implemented on the real rig as the dynamic changes occur on the system resulted from the external disturbances. Inverse RLS-AVC with gain and Inverse Neuro-AVC with gain were also considered with aim to increase total attenuation of the vibration. Comparative study among developed control schemes were compared and analysed.

## 1.3 Research Objectives

This research focuses on the development of intelligent AVC schemes for flexible beam structures. Hence, four main objectives of this study are as follows:

(1) To develop single input single output (SISO) active vibration controller for flexible beam using conventional and Inverse control strategies.

(2) To test, verify and validate the performance of all the developed controllers for vibration suppression flexible beam via simulation and experimental test using smart actuators.

(3) To develop a parametric and nonparametric identification techniques for dynamic modelling of a flexible beam structure.

## 1.4 Scope of the Research

The scope for this research comprise the following issues:

(1) In this study, fabrication of a lab-scale experimental rig to represent one edge clamped cantilever flexible beam structure with uniform cross section is constrained to transverse motion.

(2) The parametric modelling using RLS method and four types of ANN nonparametric modelling using multi-layered perceptron (MLP) network, nonlinear autoregressive with exogenous variables (NARX), ELMAN network and radial basis function (RBF).

(3) The implementation of AVC for flexible beam structure is restrained to SISO control strategy.

(4) Simulation and experimental evaluation of several AVC schemes using:

i) PID based controllers (P and PI) with non-collocated actuator-sensor configuration.

ii) Inverse RLS-AVC controller with collocated actuator-sensor configuration.

iii) Inverse Neuro-AVC controller with collocated actuator-sensor configuration.

(5) The robustness tests for proposed controllers are conducted experimentally limited to variation of disturbance amplitude range (-5 V to 10 V) and beam tip load (6 g and 12 g).

## 1.5 Contributions of the Research

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

(1) This research provides the development of AVC controller for the removal of resonance phenomenon in vibrating beam structure. Non-collocated and collocated configurations for the positions of actuator and sensor are implemented in this research. The implementations of developed controller algorithms in MATLAB Simulink are briefly explained.

(2) This study has developed several types of conventional and Inverse control strategies. These controllers are used to dampen the unwanted oscillation acting on the flexible beam structure. Comparative studies between these methods are thoroughly discussed in this study.

(3) The validity of proposed control algorithms is investigated through an experimental procedure. Test results show that the controllers are able to suppress the unwanted vibration and work well in attenuating the crucial dominant resonance modes.

## 1.6 Methodology of the Study

The complete flowchart which describes the research methodology used in this study is shown in Figure 1.1. The research begins with a critical and comprehensive literature review related to this study is conducted to identify the research gaps within this area of research.

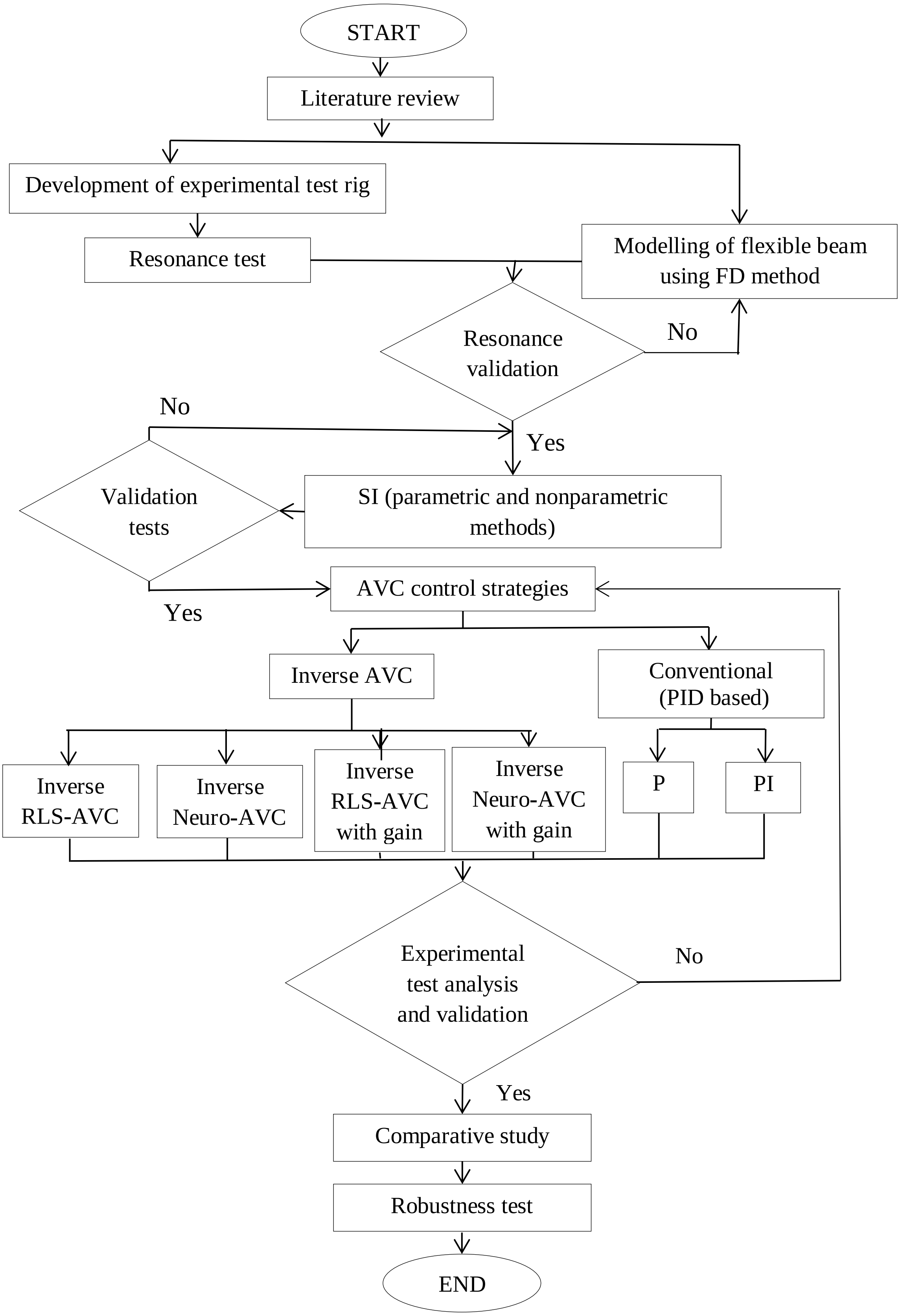


**Figure 1.1** Research procedure flowchart

### 1.6.1 Dynamic Modelling of Flexible Beam Structure

A mathematical model of flexible cantilever beam in transverse motion is developed. To control flexible beam efficiently, it is required to have an accurate dynamic model. Various approaches have been developed by previous researches for modelling the flexible beam using numerical analysis methods to solve the PDE characterising the flexible beam system's dynamic behaviour. For the purpose of this study, FD method was used. The algorithm is implemented within the MATLAB environment. For the validation purpose, predicted spectral density obtained from the model was compared with the theoretical and experimental values.

### 1.6.2 Flexible Beam Test Rig Setup

Design, fabrication and development of a lab-scale flexible beam experimental test rig. The test rig consists of an integration of mechanical and electrical components which include the flexible beam, data acquisition and instrumentation system. This test rig was used as a platform to demonstrate the performance of proposed control strategies which will be done later. Input-output data acquired experimentally was used later in Chapter 4 for the development of dynamic modelling and identification of the flexible beam structure.

### 1.6.3 SI Analysis of Flexible Beam Structure

SI using parametric RLS method and nonparametric ANN technique which determine the dynamic model that best describes input and output behaviour of the flexible beam system was presented. ANN consists of a network or circuit of biological neurons and there are classified according to their architectures. Several architectures namely MLP, NARX, ELMAN network and RBF were assessed in this study. Both parametric and nonparametric method were used in order to find the best technique that can represent the flexible beam structure. In parametric modelling, the model to fit the data is known. While for nonparametric modelling the data will define how the model should look like, thus makes it perform better in capturing hidden pattern in the data compared to parametric ones.

### 1.6.4 Validation Tests

Each model obtained from parametric and nonparametric approaches were tested their effectiveness in emulating the system's dynamic behaviour. The performance of the network was observed based on its capability to represent the system with the lowest mean squared error (MSE), one step ahead (OSA) prediction and was also validated using correlation tests.

### 1.6.5 Development of ANN AVC Controller Algorithm

Inverse RLS-AVC, Inverse Neuro-AVC, Inverse RLS-AVC with gain and Inverse Neuro-AVC with gain algorithms were developed, and its performance for flexible beam vibration suppression were simulated and compared to the conventional PID based controllers (P and PI). The non-collocated actuator/sensor configuration was adopted for P and PI controllers while collocated actuator/sensor configuration was utilised for Inverse RLS-AVC, Inverse Neuro-AVC, Inverse RLS-AVC with gain and Inverse Neuro-AVC with gain control algorithms. These developed control schemes are capable to eliminate vibration acting on the system, thus spectral attenuation can be achieved.

### 1.6.6 Experimental Test of ANN AVC Controller Algorithm

All the developed intelligent controllers were validated experimentally. Their efficiency and performance in achieving vibration suppression was observed.

### 1.6.7 Comparison Study

Lastly, both results from the simulation and experimental studies were analysed and compared thoroughly to see how well the control system reduce the vibratory disturbance on flexible beam.

## 1.7 Organisation of the Thesis

This research is organised into eight chapters. A brief outline of all the chapters are as follows:

Chapter 1 presents an introduction to the research problem. Background of this study, problems statements, objectives, scopes covered, contribution of the research and methodology of the study are all outlined in this chapter

Chapter 2 presents the literature review on identifying flexible structures using several parametric and nonparametric techniques. Next, previous works on AVC of flexible structures are addressed. Various AVC control strategies which have been developed on flexible structures are reviewed.

Chapter 3 presents the development of dynamic modelling of a flexible beam structure in two-dimensional with fixed-free ends (cantilever beam) using FD approach to characterise the plant over specific range of frequencies. The dynamic equation representing flexible beam in transverse motion is obtained. Next, the dynamic response of the flexible beam system is then simulated within MATLAB environment. The algorithm is developed in such way that disturbance can be excited at any point on the beam. Next, comparison of the modes of vibration with the theoretical value is carried out in order to ensure the validity and reliability of the proposed FD algorithm in representing the actual response of flexible beam. Detailed explanation on the experimental set-up of flexible beam test rig. All hardware used in this study is discussed in detail in this chapter. To identify the resonance frequencies of flexible

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