ACTIVE VIBRATION CONTROL OF FLEXIBLE PLATE STRUCTURE USING SMART MATERIAL

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This modest study is dedicated
To the following persons
Who have touched my life
In significant ways,
More than they'll ever know

Beloved wife,
Fatimah Hishamuddin;

Mother,
Sumingah Binti Basiran;

Father,
Jamid Bin Taruji;

Adorable brothers and sisters,
Abang Edy, Akak Lin;

Not forgotten,
Prof. Dr. Hishamuddin Bin Jamaluddin
Nor Aizan Binti Mohamad Nor

At long last, I've finally made it!

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ABSTRACT

Vibration often is one of the limiting factors in the performance of many applications and various fields such as aerospace, automotive, submarines, robotic industries, and all mechanical structures. The conventional method of suppressing the vibration is by using passive damping which consists of mounting passive material on the structure. This, however, will lead to increasing the weight of the structure and hence decreasing its performance. This research is aimed to investigate the method of vibration suppression using active vibration control approaches for the flexible plate structure. Firstly, the vibration characteristic of the plate structure is investigated. This involved a parametric identification of the vibrational flexible plate system. The Recursive Least Square algorithm was used in this study to identify the dynamic behaviour of the flexible plate. Input and output vibration signals were acquired from the flexible plate test-rig using two accelerometers as the sensors and National Instruments Data Acquisition System. The two sensors detect the vibration response along the plate caused by the excitation of the primary source (excitation point). Then, the signals are processed by on-line identification technique using Recursive Least Square estimator. The parameters for the controller are generated using the dynamic model of the system obtained from the estimator. The controlled signal is later fed to the plate to generate a superimpose signal to eliminate the unwanted vibration via smart material actuator. Finally, the performance of the Active Vibration Control algorithm developed using Recursive Least Square estimator is evaluated, verified and validated. The result demonstrates the ability of the Active Vibration Control algorithm using Recursive Least Square estimator to suppress the vibration of the flexible plate structure.

ABSTRAK

Getaran merupakan salah satu faktor penghalang dalam melaksanakan kebanyakan prestasi sesebuah aplikasi, contohnya di dalam bidang aeroangkasa, automotif, kapal selam, robot industri dan semua struktur mekanikal. Teknik konvensional dalam mengurangkan getaran adalah dengan menggunakan redaman pasif yang terdiri daripada pemasangan bahan pasif ke atas struktur seperti getah. Walau bagaimanapun, ini akan meningkatkan berat keseluruhan struktur dan akan mengurangkan prestasinya. Tujuan kajian ini adalah untuk menyiasat pengurangan getaran pada struktur plat fleksibel menggunakan sistem anti getaran secara aktif. Sebagai permulaan, ciri-ciri struktur getaran sebuah plat akan dikaji. Ini melibatkan pengangaran model menggunakan sistem parametrik bagi menghasilkan logaritma kawalan getaran pada plat fleksibel. Algoritma *Recursive Least Square* telah digunakan dalam kajian ini bagi mengenalpasti tingkah laku dinamik plat tersebut. Isyarat getaran bagi masukan dan keluaran yang diperolehi dari bahan kajian plat fleksibel akan di rakam dengan menggunakan dua meter alat pengesan dan alat sistem perolehan data. Kedua-dua alat pengesan akan mengesan getaran sepanjang plat yang disebabkan oleh alat pengetar. Kemudian, isyarat tersebut diproses secara langsung dengan menggunakan Algoritma *Recursive Least Square*. Parameter untuk pengawal ini dijana menggunkan model dinamik system yang diperolehi daripada penganggar. Isyarat terkawal kemudiannya disuap kepada plat untuk menghasilkan isyarat berlawanan untuk menghapuskan getaran yang tidak diingini melalui penggerak bahan pintar. Akhir sekali, prestasi penganggar yang telah dibangunkan mengunakan algoritma *Recursive Least Square* akan dinilai, dianalisa and disahkan. Hasil dari kajian ini telah menunjukkan keupayaan penganggar aktif sebenar untuk mengurangkan getaran pada struktur plat fleksibel.

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LIST OF ABBREVIATIONS

RLS	Recursive Least Square
LS	Least Square
AVC	Active Vibration Control
PC-Based	Personal Computer – Based
MR	Magneto – Rheological
CASA	Continuous Ant System Algorithm
ARX	Auto – Regressive with Exogenous
MSE	Mean – Squared Error
PZT	Piezoelectric
SRF	Strain Rate Feedback Control
PPF	Positive Feedback Control
PID	Proportional–Integral–Derivative Controller
RMS	Root Mean Square
MIMO	Multi Input Multi Output
AFC	Active Fibre Composite
MFC	Macro Fibre Composite
ARMAX	Autoregressive Moving Average Model with Exogenous Inputs
AR	Autoregressive
DAQ	Data Acquisition System
USB	Universal Serial Bus
I/O	Input Output
IEPE	Integrated Electronics Piezo-Electric
BNC	Bayonet Neill-Concelman (Common type of RF connector)
NI	National Instruments

FFT	Fast-Fourier Transformation
LED	Light-Emitting Diode
SISO	Single Input Single Output
C	Controller Transfer Function
OSA	One Step Ahead Prediction

LIST OF SYMBOLS

N	Newton
∞	Infinity
pH	measure of the acidity or basicity
y	System output
u	System input
w	System measured disturbance
t	Time
$y(t)$	System output at time t
$u(t)$	System input at time t
$e(t)$	System white noise at time t, random disturbance
N	The number of available data
$A(z^{-1})$	Polynomials with associated parameters of autoregressive and exogenous parts
n	The orders of polynomials of the autoregressive
m	The orders of polynomials of the exogenous parts
$v(t)$	Measurable disturbance
D(t)	Drift disturbance
z^{-1}	Backward interpolation
θ	Vector of unknown parameters
$x(t)$	Regression vector partly consisting of measured input/output
$\hat{\theta}$	Vector of adjustable model parameters
$\hat{e}(t)$	Corresponding modelling (or fitting) error at time t
J	The sum of squares of errors
$\epsilon(t)$	Error

$y(n)$	Actual output
$\hat{y}(n)$	Predicted output
$\phi_{u\varepsilon}(\tau)$	Cross-correlation function
z	Deflection on z axis
r_e	Detector located at a distance r_e relative to the primary source
d	Secondary source located at a distance d relative to the primary source
r_f	Secondary source located at a distance r_f relative to the detector
r_g	Observation point located at distances r_g relative to the primary source
r_h	Observation point located at distances r_g relative to the secondary source
E	Transfer function of the paths through r_e
F	Transfer function of the paths through r_f
G	Transfer function of the paths through r_g
H	Transfer function of the paths through r_h
M	Transfer characteristics of the detector
C	Transfer characteristics of the controller
L	Transfer characteristics of the secondary source
U_D	Primary signal at the source locations
U_C	Secondary signal at the source locations
$Y_D = Y_C$	Corresponding signal at the observation point
U_M	Detected signal
Y	Observed signal
Q_0	Secondary source is off
Q_1	Secondary source is on
$U_C=0$	Controller is on
$U_C \neq 0$	Controller is off
$\hat{\theta}(i)$	Estimation of current parameter vector
$\hat{\theta}(i-1)$	Previous estimated vector
$E(i)$	error
$P(i)$	covariance matrix

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CHAPTER 1

INTRODUCTION

1.0 Overview

Nowadays, applications of smart materials and structures have received considerable attention from many researchers. Both of these studies are currently attempts to build active structural systems to provide a necessary improvement of structural performance. Basically, smart materials can be employed as actuator and sensor which in the form of wafers, bimorph benders, and multi-layered benders (Kumar *et al,* 2007). A group of research from Boeing Company, the University of Maryland, the Massachusetts Institute of Technology, the University of California (Los Angeles) and the U.S. Army Research Office has support one projects for the development and application of this smart material application used on helicopter rotor shown in Figure 1.0. In their research, they used fibers of composite materials and piezoelectric devices on the blades of the helicopter rotor to attenuate the vibrations and also improving the aerodynamic performance (Viana *et al*, 2006).

Plate structures have been used extremely in many engineering applications because of their benefits of flexible structures such as in aerospace, automotive, submarines, robotic industries, and all mechanical structures. However, these flexibility of the plate and highly-nonlinear dynamics of the system, it's a major problem which found in industry that can lead the flexible plate to vibrate at it resonant mode (Mat Darus *et al*, 2003; Safizadeh *et al*, 2010). While in designing a structure application, plates are usually specified only to withstand applied static loads. The dynamic forces and random cyclic loads also can threaten the stability of a system. There exist a large number of discrete frequencies at which a rectangular plate will undergo large amplitude vibration by sustained time varying forces of matching frequencies. Thus, the possibility of large displacement and stresses due to this recent type of excitation must be taken into account (Tavakolpour *et al*, 2008).

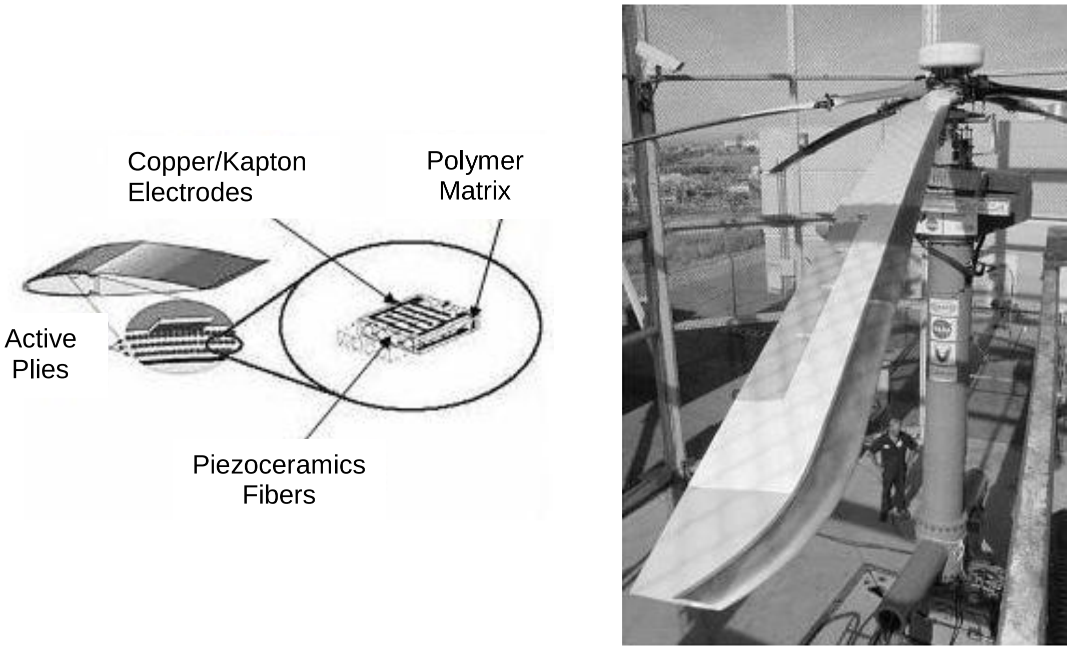

Figure 1.0: Fibers of composite materials and piezo-electric devices are used in the blades of the helicopter rotor

Practically, the aerospace composite structural constructions are relatively thin walled and become flexible. Therefore, this application is treated as lightly damped systems. During the flight, the vibration can occur from the unsteady aerodynamics in these structures. These vibrations usually take a longer time for the oscillatory energies to decay down. During this period of time the vibration in structures generally reduces their load carrying abilities and may cause fatigue and dynamic instability related to the problems. For that reason, vibration control is prefer to enhance the structural performance and also further to avoid catastrophic failures such as flutter and lifting surfaces (Kumar *et al*, 2007).

The usual method to avoid the failure of flexible plates due to vibratory disturbances is to alter the geometry or boundary conditions of the plate according to the frequency value of the vibration sources. Sometimes, it would be impossible to anticipate the frequency of disturbances owing to time dependent characteristics of the destructive vibrations. Due to this drawback, the idea of controlling the unwanted vibrations came into being. To reduce the amplitude of the destructive vibration in a structure, two control strategies, namely the passive and active methods can be employed. The passive method consists of mounting passive material on the structure. This method is relatively efficient at high frequencies but expensive and bulky at low frequencies. According to Johnson, this passive method can be divided into two classes structural and embedded. The structural damping occurs due the friction of junctions, cable rubbing and material damping. The embedded damping is achieved by adding dissipation mechanisms to the structure, commonly based on one of the following damping techniques; viscoelastic materials, viscous devices, magnetic devices and passive piezoelectric (Johnson, 1995).

The active method in controlling vibration uses the superposition of waves by generating secondary source(s) to destructively interfere with the unwanted source and thus result in a reduction in the level of vibration. This is found to be more efficient and economical than the passive method at low frequency vibration suppression (Mat Darus *et al*, 2004). To design a suitable controller for active vibration control of a flexible thin plate, it is vital to have a good understanding about the dynamics of the system. The dynamic behavior of thin isotropic rectangular plates is a subject that has received considerable attention in recent years because of its technical importance.

1.2 Background of the problem

Many effort has been done by the researcher's in order to deal with vibration alleviation in flexible structures system (Sinawi *et al*, 2004; Viana *et al*, 2006; Jnifene *et al*, 2007; Kumar *et al*, 2007; Cavallo *et al*, 2008; Tavakolpour *et al*, 2008). The potential flexible structure in various applications is leads to the highly demand, because of having reliable, lightweight and efficient of flexible structure (Mat Darus *et al*, 2003; Zhou *et al*, 2004; Ismail *et al*, 2006). However, when flexible structures are subjected to dynamic forces and random cyclic loads as well as rigid body displacements, theirs behavior presents a number of discrete frequencies at which these flexible structure will undergo large amplitude vibration by sustained time varying forces and flexible mode of vibrations (Gaudiller *et al*, 2005; Tavakolpour *et al*, 2009). Due to the advantages of flexible structures are widely has been used in various fields of applications, such as in many engineering fields on civil, mechanical, marine (Carra *et al*, 2007), aerospace engineering field (Mukherjee *et al*, 2002), and others. However, these advantages of flexible plate will be affected due to the unwanted structural vibrations. Thus, controls of flexible systems have been a challenge and have received the attention of a large number of researchers (Jnifene *et al*, 2007).

Controls of vibration of flexible structure have been studied over the past 20 years with different strategies and behavior. The conventional control methods have not been widely successful due to the dynamic complexity of flexible structure (Mat Darus *et al*, 2004). These systems reduced the vibration and noise by simply dissipating energy as heat. These conventional method is known as passive control method, consists of mounting passive material on the structure in order to change its dynamic characteristics such as stiffness and damping coefficient (Viana *et al*, 2006). Unfortunately, this method is efficient at high frequencies but expensive and bulky at low frequencies (Hossain *et al*, 1997). Passive vibration control usually leads to increase in the overall weight of structure, which makes it less transportable especially for space applications. Moreover, their damping performance is generally quite poor because they are enabling to adapt or return to changing the disturbance over time. However, conventional control is widely used because of its low cost and simplicity.

Recently, due to the technological advancements such as the availability of high-power and low cost computing, smart materials, and advanced control techniques have led to a growing use of active control such as active force control or active vibration control systems. The implication of these control strategies is that desirable performance characteristics can be achieved through the complexity of flexible structure and clever strategies, whereby actuators excite the structure based on the structure's response measured by sensors (Colla *et al*, 2009). Control of these structures involves a number of disciplines, including structural dynamics, control theory, and materials engineering. Present research focus is on developing control of flexible structure systems, incorporating conventional based identification, to overcome the above-mentioned problems.

1.3 Statement of the problems

Vibration is often a limiting factor in performance of many fields application. Many precision industrial processes in the fields of aerospace, ground transportation, agriculture, measurement, life sciences, semiconductor industry and nanotechnology cannot take place if the equipments are being affected by vibration. The conventional method of decreasing the vibration level is to use passive damping which consist of mounting passive material on the structure.

The aim of this research is to investigate and develop the active vibration control systems of a flexible structure and to validate the controller performance by experimental study. This study is focused on the flexible structure than rigid structures as they are capable of being operated at high speeds and handling of a larger payloads with the same actuator capabilities (Hossain *et al*, 1995). Flexible structure with several boundary conditions will be considered. Firstly, by understanding the dynamic characteristics and mode classification of the flexible structure, it will be useful tool to assist for the development of the control strategies (Ismail *et al*, 2006).

A schematic diagram of the SISO feed-forward AVC structured has been considered in this study due to understanding the dynamics characteristics and mode of vibration of the flexible structure (Hossain *et al*, 1995; Tokhi *et al*, 1997). A dynamic response of the structure is developed through an experimental study. Thus, the system has been introduced structural vibration at (primary) point source into the structure systems. The dynamics response then were detected by a sensor and thus signal is fed to an actuator (secondary) point source for generation of the superimposed signal on the primary signal to achieve vibration reduction at the observation point (Mat Darus *et al*, 2004).

In order to design an active controller for the vibration suppression, the identification system has been used in order to find an accurate model of the systems. A conventional method for identification system such as Least Squares (LS) and Recursive Least Squares (RLS) have been considered (Mat Darus *et al*, 2004).

1.4 Objectives

The objectives of this research are to:

1. Develop an active vibration control algorithm for vibration suppression of a flexible plate structure.

2. Develop an experimental rig for the implementation of an active vibration control of the flexible plate structure.

3. Implement and validate thus developed an active vibration control algorithm on the developed experimental rig.

1.5 Scope of the study

The following are the scope of the study:

1. Development of flexible plate structure rig. The experimental rig has been setup employing mechatronic approaches. Actuator and sensor were attached to the experimental rig such as electromagnetic shaker, piezoelectric sensor/actuator, and accelerometer.

2. Development of an electromagnetic shaker as the primary disturbance for the plate structure.

3. Data collection using PC-Based equipment such as data acquisition system and analyzer.

4. The system identification of the plate structure using conventional parametric modeling technique such as Recursive Least Squares (RLS) were carried out.

5. Development of a conventional an active vibration control system.

6. Testing and verification of the developed active vibration control technique through experimental validation.

7. Comparative assessment of the experimental result with the simulation result.

1.6 Methodology of the study

This research focused on the development of an active vibration control techniques based on system identification methods for vibration suppression of flexible structures by experimental studied. The methodologies of the study were divided into four major sections:

a) *Literature Review* – This section discussed reviewed on active vibration control, smart structure, smart material, system identification, control strategy and self-tuning control.

b) *Parametric Identification* – This section discussed on the model selection, model estimation, model validation & implementation, and results with difference excitation input.

c) *Experimental Study* – This section discussed on the experimental rig hardware and software, equipment preparation, experimental setup and experimental procedure.

d) *Active Vibration Control (AVC)* – This section discussed on the control design of AVC, model estimator on system identification, implementation of the controller using online identification in self-tuning of AVC.

The flowchart of the research can be clearly seen in step by step process as shown in Figure 1.2.

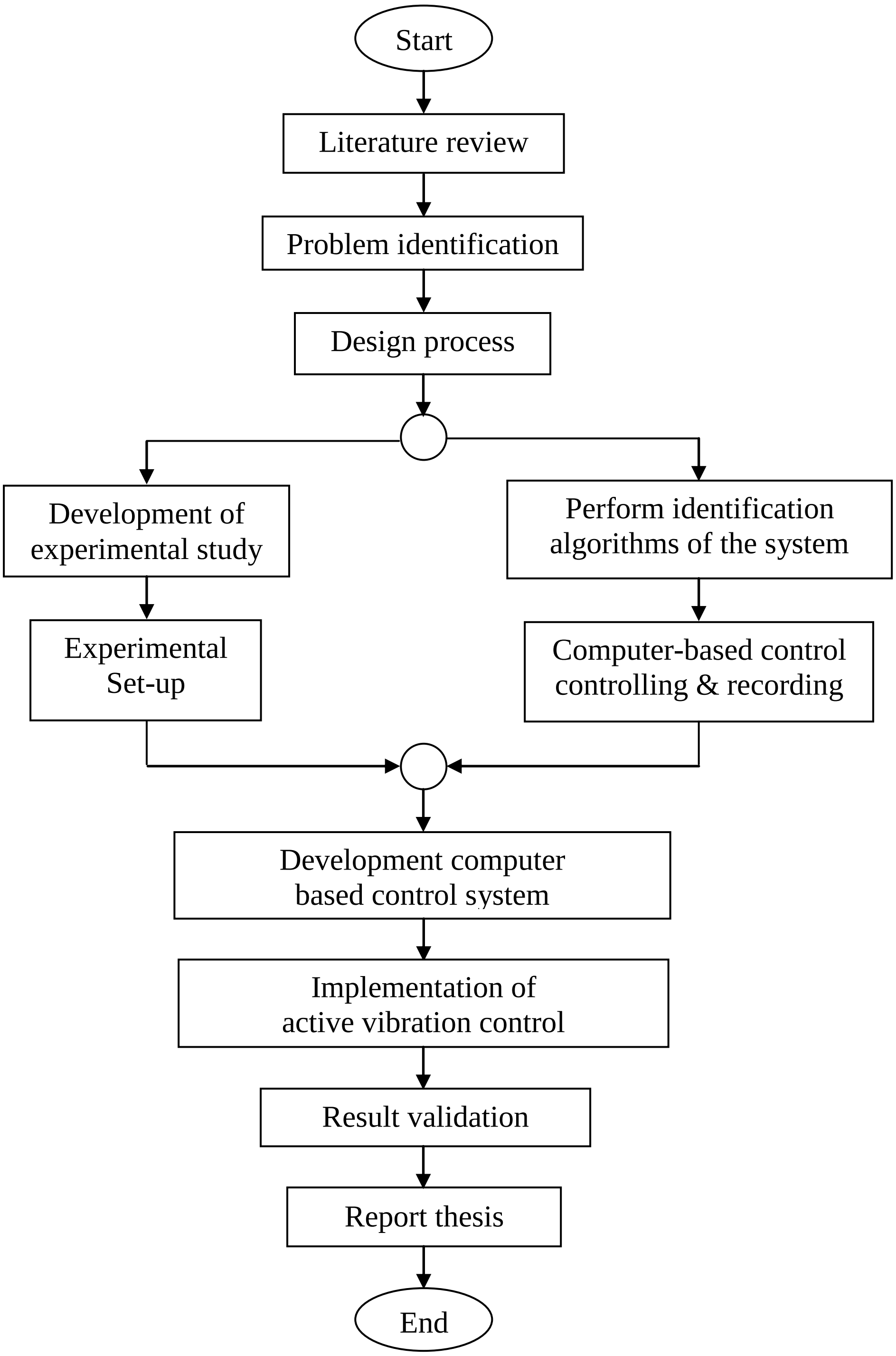

Figure 1.2: Project flow chart

1.7 Gantt chart

	2009						2010												2011											
	J	A	S	O	N	D	J	A	J	A	S	O	N	D	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Literature review	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Problem identification	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■										
Development of the experimental rig		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■										
Development of the electromagnetic shaker					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■										
System Identification of the system									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						
AVC controller development (simulation)											■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					
Implementation of AVC controller													■	■	■	■	■	■	■	■	■	■	■	■	■					
Test & verification																		■	■	■	■	■	■	■	■	■				
Evaluation of the performance of the algorithm on the experimental rig																						■	■	■	■	■	■			
Report writing					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

1.8 Summary

Background and statement of the problem in this research has been discussed and considered. The outcomes of this research are including a complete research on the system identification of the plate structure using conventional parametric modeling techniques as known as Recursive Least Square (RLS), development and experimental validation of the Active Vibration Control Strategy for vibration suppression of the flexible plate system.

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2. 4th Asia International Conference on Mathematical Modelling & Computer Simulation, (26-28 May 2010 Kota Kinabalu, Sabah, Borneo Island, Malaysia) Neuro-Modelling of Flexible Plate Structure Rig for Active Vibration Control Algorithm, I. Z. Mat Darus, A.A.M.Al-Khafaji and M.F.Jamid.

3. 1st International Conference on (Energy, Power and Control)(30 November 2010 Basra, Iraq), ANFIS Modelling of Flexible Plate Structure, I. Z. Mat Darus, A.A.M.Al-Khafaji and M.F.Jamid.