EVOLUTIONARY SWARM ALGORITHM FOR MODELLING AND CONTROL OF HORIZONTAL FLEXIBLE PLATE STRUCTURES

MUHAMAD SUKRI BIN HADI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

DECEMBER 2017

In the name of Allah, The Most Beneficent, The Most Gracious, The Most Merciful

A lot of thanks

To my beloved parents Hadi bin Ismail and Mariah binti Md Amin and my siblings who are always praying for me and brought a great motivation for the completion of my studies.

To my respectable supervisor Assoc. Prof. Dr. Intan Zaurah Mat Darus for her kindness, boundless guidance and endless patience.

ACKNOWLEDGEMENT

In the name of Allah, the Most Gracious, the Most Merciful. All the praises and thanks be to Allah, who gave me the knowledge, healthy life, determination and endless patience to accomplish this research.

I would like to express my deepest gratitude to my research supervisor, Assoc. Prof. Dr. Intan Zaurah binti Mat Darus for her continuous valuable advice, knowledge, guidance, patience and generous amount of time for assisting me due to give the smooth journey in completing this research. Having her as a research supervisor is the highest privilege where her professionalism of handling my weakness has changed the simplistic mind of mine into critical view. My gratitude is also extended to my external supervisors, Dr. Mohammad Osman Tokhi for his constant encouragement and patience in guiding me during my research attachment in the University of Sheffield.

I am indebted to Ministry of Higher Education (MOHE), Universiti Teknologi MARA (UiTM) and Universti Teknologi Malaysia (UTM) for funding my PhD study as well as providing the research facilities and grant. Librarians and staffs at UTM and University of Sheffield also deserve special thanks for their assistance in preparing the relevant literatures and supports.

Sincere appreciation goes to my fellow postgraduate friends in Active Vibration Control Research Group, especially to Mr. Rickey Ting and Dr. Hanim who give me endless support and knowledge throughout in the completion of this research. Last but not least, my utmost appreciation goes to my beloved family, without their endless sacrifices, prayers, patience and constant love, I would never reach this level.

ABSTRACT

Numerous advantages offered by the horizontal flexible structure have attracted increasing industrial applications in many engineering fields particularly in the airport baggage conveyor system, micro hand surgery and semiconductor manufacturing industry. Nevertheless, the horizontal flexible structure is often subjected to disturbance forces as vibration is easily induced in the system. The vibration reduces the performance of the system, thus leading to the structure failure when excessive stress and noise prevail. Following this, it is crucial to minimize unwanted vibration so that the effectiveness and the lifetime of the structure can be preserved. In this thesis, an intelligent proportional-integral-derivative (PID) controller has been developed for vibration suppression of a horizontal flexible plate structure. Initially, a flexible plate experimental rig was designed and fabricated with all clamped edges boundary conditions at horizontal position. Then, the data acquisition and instrumentation systems were integrated into the experimental rig. Several experimental procedures were conducted to acquire the input-output vibration data of the system. Next, the dynamics of the system was modeled using linear auto regressive with exogenous, which is optimized with three types of evolutionary swarm algorithm, namely, the particle swarm optimization (PSO), artificial bee colony (ABC) and bat algorithm (BAT) model structure. Their effectiveness was then validated using mean squared error, correlation tests and pole zero diagram stability. Results showed that the PSO algorithm has superior performance compared to the other algorithms in modeling the system by achieving lowest mean squared error of 4.3947×10^{-6}, correlation of up to 95 % confidence level and good stability. Next, five types of PID based controllers were chosen to suppress the unwanted vibration, namely, PID-Ziegler Nichols (ZN), PID-PSO, PID-ABC, Fuzzy-PID and PID-Iterative Learning Algorithm (ILA). The robustness of the controllers was validated by exerting different types of disturbances on the system. Amongst all controllers, the simulation results showed that PID tuned by ABC outperformed other controllers with 47.60 dB of attenuation level at the first mode (the dominant mode) of vibration, which is equivalent to 45.99 % of reduction in vibration amplitude. By implementing the controllers experimentally, the superiority of PID-ABC based controller was further verified by achieving an attenuation of 23.83 dB at the first mode of vibration and 21.62 % of reduction in vibration amplitude. This research proved that the PID controller tuned by ABC is superior compared to other tuning algorithms for vibration suppression of the horizontal flexible plate structure.

ABSTRAK

Pelbagai kelebihan ditawarkan oleh struktur melintang boleh lentur telah menarik penambahan penggunaan industri di dalam banyak bidang kejuruteraan terutamanya pada sistem penghantar bagasi lapangan terbang, pembedahan mikro tangan dan industri pembuatan separuh pengalir. Namun, struktur melintang boleh lentur ini sering dikenakan daya gangguan disebabkan getaran dengan mudah berlaku di dalam sistem. Getaran mengurangkan prestasi sistem, maka membawa kepada kegagalan struktur apabila tegasan dan kebisingan berlebihan terhasil. Dengan demikian, ia adalah penting untuk meminimumkan getaran tidak dikehendaki mengakibatkan keberkesanan dan jangka hayat struktur boleh dipelihara. Di dalam tesis ini, sebuah pengawal berkadaran-kamiran-terbitan (PID) pintar telah dibina untuk menghapuskan getaran terhadap sebuah struktur plat melintang boleh lentur. Pada mulanya, sebuah rig eksperimen plat boleh lentur direka bentuk dan dibina dengan syarat sempadan semua bucu diapit pada kedudukan mendatar. Kemudian, sistem perolehan data dan instrumentasi dipasang ke dalam rig eksperimen. Beberapa tatacara eksperimen dilaksanakan untuk memperolehi data masukan-keluaran getaran plat melintang boleh lentur. Seterusnya, sistem dinamik dimodelkan menggunakan automundur lelurus dengan masukan luar kawalan, dioptimum dengan tiga jenis algoritma kerumunan evolusi, iaitu struktur model pengoptimuman kerumunan zarah (PSO), koloni lebah tiruan (ABC) dan algoritma kelawar (BAT). Keberkesanannya telah disahkan menggunakan ralat min kuasa dua, ujian korelasi dan rajah kestabilan kutub-sifar. Keputusan menunjukkan algoritma PSO mempunyai prestasi lebih baik berbanding algoritma lain di dalam pemodelan sistem dengan memperolehi ralat min kuasa dua terendah 4.3947×10^{-6}, korelasi sehingga 95 % aras keyakinan dan kestabilan yang baik. Seterusnya, lima jenis pengawal PID dipilih untuk menghapus getaran tidak dikehendaki, iaitu, pengawal PID-Ziegler Nichols (ZN), PID-PSO, PID-ABC, kabur-PID dan PID-algoritma pembelajaran berlelaran (ILA). Ketegapan pengawal disahkan dengan mengenakan jenis gangguan yang berbeza terhadap sistem. Antara semua pengawal, keputusan simulasi menunjukkan pengawal PID ditala menggunakan ABC mengatasi pengawal lain dengan 47.60 dB aras pengecilan pada mod getaran pertama (mod dominan), bersamaan 45.99 % pengurangan amplitud getaran. Dengan melaksanakan pengawal secara eksperimen, keunggulan pengawal PID-ABC disahkan lagi dengan memperolehi 23.83 dB pengecilan pada mod getaran pertama dan 21.62 % pengurangan amplitud getaran. Penyelidikan ini membuktikan bahawa pengawal PID ditala oleh ABC lebih baik berbanding dengan talaan algoritma lain untuk penghapusan getaran struktur plat melintang boleh lentur.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ABC	-	Artificial bee colony
AC	-	Alternating current
ADRC	-	Auto-disturbance rejection control
AFCILA	-	Active force control based active vibration control
AGV	-	Automatic guided vehicle
AISC-ASD	-	American Institute of Steel Construction-Allowable Stress Design
AMB	-	Active magnetic bearing
ANFIS	-	Adaptive network-based fuzzy inference system
APSO	-	Adaptive particle swarm optimization
ARX	-	Auto-Regressive with exogenous
ASCENTB	-	Ascension path of boiling water
AVC	-	Active vibration control
AVCILA	-	Iterative learning based active vibration control
AVCGA	-	Genetic algorithm based active vibration control
AVR	-	Automatic voltage regulator
BAT	-	bat algorithm
CCCC	-	Clamp-clamp-clamp-clamp
CCFF	-	Clamp-clamp-free-free
DAQ	-	Data acquisition system

DC	-	Direct current
DE	-	Differential evolution
DOF	-	Degree of freedom
EBA	-	Enhanced bat algorithm
ENN	-	Elman neural networks
ICSPSO	-	Hybrid between cuckoo search and particle swarm optimization algorithms
ILA	-	Iterative learning algorithm
ILC	-	Iterative learning control
IO	-	Integer order
F-PID	-	Fuzzy- proportional-integral-derivative controller
FDM	-	Finite difference method
FEM	-	Finite element method
FIS	-	Fuzzy inference system
FLANN	-	Functional link artificial neural network
FOPID	-	Fractional order proportional integral derivative
GA	-	Genetic algorithm
HJPSO	-	Hybrid jump particle swarm optimization
ISE	-	Integral square error
LB	-	limit range of search boundary
LFC	-	Load frequency control
LMI	-	Linear matrix inequality
LQC	-	Linear quadratic Gaussian
LVDT	-	Linear variable differential transformer
MF	-	Memberships functions

MLPNN	-	Multi-layer perceptron neural networks
MPC	-	Model predictive controllers
MSE	-	Mean squared error
NB	-	Number of bee colony size
NI	-	National Instrument
NP	-	Number of particles
OKID	-	Observer/Kalman filter identification
OSA	-	One step-ahead prediction
PDE	-	Partial differential equation
PDILC	-	Proportional differential iterative learning control
PID	-	Proportional-integral-derivative controller
PID-ABC	-	Proportional-integral-derivative controller tuned by artificial bee colony algorithm
PID-ILA	-	Proportional-integral-derivative controller tuned by iterative learning algorithm
PID-PSO	-	Proportional-integral-derivative controller tuned by particle swarm optimization
PID-ZN	-	Proportional-integral-derivative controller tuned by Ziegler-Nichols
PM	-	Pneumatic muscle
PMSM		Permanent magnet synchronous motor
PSO	-	Particle swarm optimization
PZT	-	Lead Zirconate Titanate
STAAD	-	Structural analysis and design computer program
TS	-	Torsion spring
UPFC	-	Unified power flow controller

LIST OF SYMBOLS

$A(z^{-1})$	-	Polynomials parameters of autoregressive
A_i	-	The error of fuzzy set
A_{mean}^{t}	-	The average loudness of all bats
$a_{1...}a_n\ b_1...b_n$	-	Unknown system parameters
B_j	-	The change in error for fuzzy set
$B(z^{-1})$	-	Polynomials parameters of autoregressive
$\beta \in [0,1]$	-	Random vector drawn from a uniform distribution
C_{ij}	-	The proportional linguistic variables
c_1, c_2	-	Acceleration coeffiecients
D_{ij}	-	The integral linguistic variables
$\delta(\tau)$	-	An impulse function
$e(t)$	-	The residual
$e(t)$	-	Predicted error at time
E_{ij}	-	The derivative linguistic variables
E	-	Young's modulus
Fx	-	Axial force
Fy	-	Structure shear
$f_{\min}$	-	Frequency minimum
$f_{\max}$	-	Frequency maximum
$f(.)$	-	Nonlinear function

$gbest$	-	Overall best position of all particles
I	-	Moment of inertia
K_p	-	Proportional gain
K_i	-	Integral gain
K_d	-	Derivative gain
$K(k+1)$	-	New value updated into the memory
$K(k)$	-	The value in the memory from the previous iteration
$K(k+1)$	-	New value updated into the memory
$K(k)$	-	The value in the memory from the previous iteration
L	-	Length
Mx	-	Structure torsion
Mz	-	Structure bending
n	-	Order of the model
$N(\theta)$	-	Nectar amount
$pbest$	-	Particles best position
ρ	-	Mass density per area
P_i	-	Probability of food source located
$rand$	-	Random number
$r_i \in [0,1]$	-	Pulse rate
R_k	-	The condition of fuzzy control
T	-	Thickness
T_u	-	Oscillation period
t	-	Number of iterations
u	-	Model input
$u(t)$	-	Discrete input

v_i	-	Velocity
ν	-	Poison ratio
w	-	Inertia weight
w_{max}	-	Maximum values of inertia weight
w_{min}	-	Minimum values of inertia weight
w	-	Width
x_i	-	New position in the search space
x_{new}	-	Current global best solution
$x_{\min}, x_{\max}$	-	Domain size of the interested problem
$y(t)$	-	Discrete output
$y(d)$	-	Desired output
$y(k)$	-	Actual output
y	-	Model output
$\hat{y}(t)$	-	One step-ahead estimated model output at time
$y(n)$	-	Actual output of the system
z^{-1}	-	Back shift operator
$\xi(t)$	-	Zero mean white noise
θ_i	-	Position of *i*th food sources
$\theta_i(c+1)$	-	New position of *i*th food sources
$\phi_i(c)$	-	Random step
φ	-	Random vector drawn from a uniform distribution
$\phi_{ee}(\tau)$	-	Auto correlation
$\phi_{ue}(\tau)$	-	Cross correlation
Φ	-	Learning parameter

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Over the past decade, problems related to vibrations have been reported in many applications such as aerospace, marine, automotive, electrical machine and civil structures. These problems occur due to many industries have shown interest in employing light weight, stronger and more flexible structures in their engineering applications such as in the airport baggage transport conveyor, micro hand surgery system and semiconductor manufacturing industry. The advantages of flexible structures which are light, reliable and efficient make many industries employ these flexible structures rather than using rigid structures. Beyond the advantages, it also has its downside. For instance, the light weight characteristic of flexible structures can be easily influenced by the vibration and it also brings several problems including instability, fatigue, bending and low performance. Therefore, it is compulsory to suppress the unwanted vibration of flexible structures.

Many attempts have been proposed by the researchers in order to reduce the vibration by considering several control strategies. The simplest strategy in reducing the vibration is to build more rigid structure so that less vibration will be produced. Nevertheless, this strategy is usually not applicable. Passive control strategy has also been approached by applying passive materials like vibration damper and dynamic observer. However, this method is only applicable for high frequencies range, but not working well for low frequency range. Moreover, in meeting the demand of engineering applications, many industries are putting efforts to keep the structural weight as low as possible, thus making the passive solutions nonviable (Christopher, 2007). In reality, it becomes a growing trend among the industry to reduce the weight of mechanical structures especially in the spacecraft and aircraft engineering. When a lighter or weaker structure is used, it will indirectly reduce the cost. However, it makes the structure more flexible which may destruct its structural performance.

A general method to prevent the failure of flexible plate structure due to external disturbances is by altering the geometry or boundary conditions of the plates. The alteration is based on the frequency of vibration sources. However, it would be impossible to anticipate the frequency of disturbances due to time dependent characteristic of the destructive vibrations. Because of this difficulty, it brings the idea to control the unwanted vibration using passive and active control methods. Nevertheless, the passive control method has two major obstacles which are ineffective at low frequency range (Tokhi and Hossain, 1996; Hossain and Tokhi, 1997; Jnifene, 2007) and only efficient for a narrow band of frequency. Despite some novel passive control method namely its very light characteristic that has been addressed by Hagood and Flowtow (1991) and Bisegna *et al.* (2006), it is ineffective for a broad band of frequency control.

In fact, an active vibration control (AVC) method is more efficient, reliable and flexible in controlling the unwanted vibration of flexible structure. The potential of active vibration has been received remarkable attention from the researchers due to many applications that demand for effective vibration suppression especially in the aerospace structure, flexible robotic arms and micro mechanical systems. AVC is a method to reduce the amplitude of the unwanted vibration by introducing the secondary sources of vibration to the dynamical system (Tokhi and Hossain, 1996). This AVC concept was introduced by Lueg in 1936 for noise cancellation. As stated by Mat Darus and Tokhi (2005), AVC is employed using the superposition of waves, by introducing the secondary vibration sources to the vibration at the desired location. This method is found to be more economical and effective for the vibration suppression of flexible structure as compared with the passive control method, especially at low frequency range.

1.2 Problem Statement

The plate structures are currently used in the industries are heavy and strong metal leads to stable performance. However, the major disadvantages of rigid plate structures are need high power consumption and limitation in operation speed. Furthermore, it becomes a growing trend among the industries to reduce the weight of mechanical structures due to reduce the production cost and to increase the system effectiveness. In recent times, the characteristics offered by the flexible plate structure such as lightweight, faster response, less power consumption and less bulky design have received significant considerations by the industries to apply its advantages into their engineering applications (Tokhi and Azad, 2008 and Mahamood, 2012).

Nevertheless, the vibration of the flexible plate structure is a critical problem faced by the industries, particularly in the airport baggage transport conveyor, micro hand surgery system and semiconductor manufacturing industry which have a light weight characteristic and relatively low damping for the fundamental and initial models. This drawback is often a limiting factor in the structure performance that can lead to the instability, fatigue and structural damages (Tavakolpour, 2010). Moreover, the frequency associated with this structure is commonly low which makes the nodes vibration control become an important issue for the light flexible structures (Saad, 2014).

Then, one of the famous methods has been applied by the researchers to overcome the problem regarding the vibration of the flexible plate structure is known as active vibration control (AVC) technique (Tavakolpour, 2010; Saad 2014; Mohd Yatim; 2016 and Al-Khafaji, 2016). Although several studies have been conducted by previous researchers about AVC for flexible plate structure, it is still an open area of research due to the complex dynamic of flexible structures. Most of the previous researchers in their studies are focused on flexible plate in vertical position with different boundary conditions (Zhi *et al.*, 2009; Tavakolpour, 2010; Jamid, 2010 and Rahman, 2012). Hence, this thesis will concentrate on the vibration suppression of the square, flexible thin plate with all edges clamped boundary conditions in horizontal position.

Besides, many researchers have acquired the input-output data of the flexible plate through simulation works via finite difference and finite element methods. This does not represent the real characterization of the flexible plate itself (Mat Darus, 2004; Schedin *et al.*, 1999; Wang and Lai, 2000; Caruso *et al*., 2003). Thus, the input-output vibration data of the flexible plate will be collected experimentally in this study. Finding a suitable model for the dynamic system is compulsory so that a better control performance can be achieved (Mat Darus and Al-Khafaji, 2012; Saad, 2014).

In addition, the evolutionary swarm algorithms namely particle swarm optimization, artificial bee colony and bat algorithm are developed in this research in order to obtain an approximate dynamic model that represented the real characterization of the system. For instance, particle swarm algorithm has efficient global search and simple parameters which brings the algorithm into fast speed convergence (Kennedy and Eberhart, 1995). Meanwhile, artificial bee colony algorithm has wide exploration in searching for optimal solution, and bat algorithm has the capability of automatically zooming into the founded solution region (Karaboga, 2005 and Yang, 2010b). Motivated by its capabilities, thus, the system modelling and controller optimization based on evolutionary swarm algorithm will be implemented in this research.

The best model that represents the system will be selected and used as a controller development platform later on. Besides, the tuning of PID controller using conventional and intelligent methods is applied on the identified model using the system identification technique for vibration suppression of flexible plate system. All of the proposed controllers in this study will be developed in a simulation environment and implemented into the experimental rig as an experimental validation of the developed controllers performance.

1.3 Research Objectives

The objectives of this study are as follows:

1. To develop mathematical models of horizontal flexible plate system with all edges clamped using system identification via evolutionary swarm algorithms using the actual input-output experimental vibration data.

2. To design and simulate intelligent Proportional-integral-derivative (PID) controller for vibration suppression of all edges clamped in horizontal flexible plate structure based on identified model.

3. To validate and verify the developed controllers experimentally using self-developed magnetic shaker actuator and to compare its performances for the suppression of the unwanted vibration of all edges clamped in horizontal flexible plate structure.

1.4 Research Scope

The scopes of this study are listed as follows:

1. The experimental rig is designed using SolidWorks software, analyzed using STAAD Pro 2004 software and fabricated.

2. The experimental rig is designed using horizontal flexible plate structure with all edges clamped boundary condition only.

3. The design and integration of a data acquisition with an instrumentation system to acquire the input-output vibration data from the experimental rig and later to validate the developed controller experimentally.

4. Modelling of all edges clamped horizontal flexible plate models using evolutionary swarm algorithms via particle swarm optimization (PSO), artificial bee colony (ABC) and bat algorithm (BAT) only.

5. Development of active vibration controller algorithms via conventional method known as PID controller tuned by Ziegler Nichols and intelligent methodologies such as PID controller tuned by swarm intelligence algorithms (PSO and ABC), Fuzzy-PID controller and PID-iterative learning algorithm (ILA) controller. The performance of the developed controllers is assessed by evaluating their capability to suppress the unwanted vibration of the first vibration mode only.

6. The objective function used in the PSO and ABC algorithms to tune the PID controller is limited to single objective function based on lowest mean square error.

7. Implementation is limited to four different types of disturbances only on the developed controller which are sinusoidal, multiple sinusoidal, real and multiple real disturbances.

8. Experimental validation based on the best control schemes performance which obtained through the simulation works is conducted on the developed horizontal flexible plate test rig. Magnetic shaker is applied as a disturbance and actuator during the experimental works.

1.5 Research Contribution

The main contributions of this research are explained briefly as follows:

1. The evolutionary swarm algorithm was implemented in this research for modelling the dynamic characterization of an all clamped edges boundary

conditions in horizontal flexible plate system. The parametric optimizations known as Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC) and Bat Algorithm (BAT) with Auto-Regressive with Exogenous (ARX) model structure were proposed for modelling the plate system. The modelling was developed based on the real experimental vibration data that has been acquired through the experimental rig. The validation of the developed models were compared and assessed in terms of the lowest mean squared error (MSE), one step-ahead prediction, correlation tests and pole-zero diagram stability.

2. This study provides detailed implementation of evolutionary swarm algorithm for tuning the PID controller using PSO and ABC algorithms that has not previously reported in controlling the unwanted vibration of the horizontal flexible plate. The algorithms were tuned in order to achieve the best vibration suppression of the horizontal flexible plate system. The hybrid controllers known as fuzzy-PID controller and PID-Iterative learning algorithm (PID-ILA) controller were developed to suppress the unwanted vibration. The performance of the control schemes is observed in vibration suppression of the horizontal flexible plate system at the first vibration mode.

3. Based on active vibration control (AVC) technique, the proposed control schemes in this research were validated by implementation on the developed experimental rig. This is a good platform for the evaluation and assessment of the proposed control schemes as well as self-developed of the actuation system namely magnetic shaker in suppressing the unwanted vibration of horizontal plate system. Two magnetic shakers were used as source of disturbance and actuation system for experimental validation purpose of the study. The attenuation of the first vibration mode obtained through the experiment was compared with simulation works.

1.6 Research Methodology

The research was first carried out with the extensive and inclusive literature review on flexible plate structure at the horizontal position with all edges boundary condition. An experimental rig of horizontal flexible plate was designed, analyzed and fabricated due to collect the input-output vibration data experimentally. The instrumentation and data acquisition systems were designed and integrated into the experimental rig. Then, the input-output vibration data obtained was then utilized to develop the dynamic model of the system using system identification via evolutionary swarm algorithm. For this research, the system identification was conducted within MATLAB programming environment using three different types of algorithms. Later, the intelligent PID controller was developed based on identified model via simulation work. Five different types of controllers were developed and validated using four different types of disturbances in the system. Finally, two best controllers achieved in the simulation works were utilized to be used on the experimental rig as a validation of the developed controller. Several tests were conducted in order to verify the robustness of the controller. Details for methodology used in this research as discussed in Chapter 3.

1.7 Organization of the Thesis

This thesis is organized into 7 chapters. A brief outline of the thesis is summarized as follows:

Chapter 1 presents the research introduction. It includes background of the study, problem statement, objectives and scopes of the research. The research methodology flowchart and research contribution are also highlighted in this chapter.

Chapter 2 reveals the literature review related to the research. The literature review focuses on the modelling approaches and active vibration control of flexible structure from the previous works. A brief overview on the development of flexible structure experimental test rig and horizontal flexible plate are reviewed. Besides, the research on PID tuned by PSO and ABC algorithms as well as hybrid controller using Fuzzy-PID and PID-ILA controllers for the recent applications are also emphasized. Then, the gaps of this study are also identified.

Chapter 3 discusses the development of experimental test rig and experimental set up to perform horizontal flexible plate experiment as well as to assess the effectiveness of the proposed control scheme experimentally. The designs and fabrication of experimental rig are elaborated. In addition, the experimental devices, instrumentation, data acquisition system and software of the experimental setup for vibration data collection purpose are presented. The integration of instrumentation and data acquisition system into experimental test rig are explained. This chapter also reveals the impact tests that have been conducted to identify the dominant mode of the horizontal flexible plate system.

Chapter 4 focuses on the development of system identification via intelligent swarm algorithm of horizontal flexible plate system. The system is developed based on acquired actual vibration data through experimental test rig. Three types of intelligent swarm algorithms were selected to obtain the unknown parameter of the ARX model structure, namely PSO, ABC and BAT algorithms. Thus, the details of the proposed algorithm are also elaborated in this chapter. The developed models were then validated in terms of mean squared error, one step ahead predication, correlation test and pole-zero diagram stability. A comparative study among the developed algorithms in identifying the best system model is illustrated.

Chapter 5 devotes the active vibration control of horizontal flexible plate system in the simulation work. The conventional and intelligent control strategies have been proposed in this chapter to determine an optimal PID parameters of horizontal flexible plate system. The objective of the developed controller is to achieve high attenuation vibration and lowest mean squared error in the system. Furthermore, the PID controller is tuned using Ziegler-Nichols, PSO, ABC, fuzzy and iterative learning algorithms. The robustness of the controllers via four types of disturbances are validated. Therefore, the comparative performance among the controllers is presented.

Chapter 6 validates the performance of the developed controller in simulation work for vibration suppression on the experimental test rig. Two best controllers in the simulation work were tested in the experiment particularly PID-PSO and PID-ABC based controllers. The controller performance is observed and evaluated based on high attenuation achieved in suppressing the unwanted vibration of the horizontal flexible plate system. The best placement of magnetic shaker actuator location on the experimental test rig is also considered. The robustness of the controller by varying the amplitude disturbances and additional mass payloads in the vibrating system is highlighted.

Chapter 7 summarizes the presented work and conclusions. Future works and recommendations regarding modelling and vibration cancellation of the flexible plate system are outlined in this chapter.

REFERENCES

Abedinia, O., wyns, B. and Ghasemi, A. (2011). Robust Fuzzy PSS Design using ABC. *10th International Conference on Environment and Electrical Engineering (EEEIC)*, Rome, Itali. 8-11 may 2011. 1-4.

Abdullah, M. Y., Hussien, M., Md Zain, M. Z., Ahmad, R. and Ganesh, R. (2008). Effect of Transducer Mass on Thin Plate Vibration. *International Symposium on Information Technology*. 26-28 August. Kuala Lumpur, Malaysia.

Abdullah, M. A., Ahmad, S. and Toha, S. F. (2015). Particle Swarm Optimization-Based Identification of a Bouncing Spherical Robot. *10th Asian Control Conference*. 31 May-3 July. Sabah, Malaysia.

Agyei-Agyemang, A. and Akangah, P. (2008). Optimisation of Plate Thickness Using Finite Difference Method. *Journal of Science and Technology*. 28(3), 197-203.

Ahn, H. - S., Chen, Y. Q., 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.

Alam, M. S. and Tokhi, M. O. (2007). Dynamic Modelling of a Single-Link Flexible Manipulator System: a Particle Swarm Optimisation Approach. *Journal of Low Frequency Noise, Vibration and Active Control*. 26, 57-72.

Alfi, A. and Modares, H. (2010). System Identification and Control using Adaptive Particle Swarm Optimization. *Journal of Applied Mathematical Modelling*. 35, 1210–1221.

Al-Khafaji, A. A. M. (2010). *System Identification of Flexible Plate Structure.* Master Thesis Department of Applied Mechanics, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia.

Al-Khafaji, A. A. M. (2016). *Modeling and Control Of Underwater Flexible-Link Manipulator Employing Bio-Inspired Algorithms and PID-Based Control Schemes*. Ph.D. Thesis Department of Applied Mechanics, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia.

Al-Talabi, A. A. and Schwartz, H. M. (2014). A Two Stage Learning Technique Using PSO-based FLC and QFIS for the Pursuit Evasion Differential Game. *Proceeding of IEEE International Conference on mechatronic and Automation*, Tianjin, China, 3-6 August 2014. 762-769.

Amin, S. H. M. and Andriansyah, A. (2006). Particle Swarm Fuzzy Controller for Behavior-based Mobile Robot. *9th International Conference on Control, Automation, Robotics and Vision (ICARCV),* Singapore. 5-8 December 2006. 1-6.

Araki, S. and Deguchi, I. (2012). Prediction of Wave force Acting on Horizontal Plate above Still Water Level. *Coastal engineering Proceedings*. 33, 1-12.

Astrom, K. J. and Hagglund, T. (1998). *Automatic Tuning of PID Controllers*. Instrument Society of America.

Astrom, K. J. and Hagglund, T. (2006). *Advanced PID Control*. Research Triangle Park, N. C.: Instrumentation, System and Automation Society.

Aula, A., Ahmad, S. and Akmeliawati, R. (2015). PSO-Based State Feedback Regulator for Stabilizing a Two-wheeled Wheelchair in Balancing Mode. *10th Asian Control Conference*. 31 May-3 July. Sabah, Malaysia.

Baskar, M. W. I. S. Evolutionary Algorithms based Design of Multivariable PID controller. *Journal of Expert Systems with Applications*. 36, 9159-9167.

Bendjeghaba, O., Ishak, B. S. and Zemmour, N. (2013). Firefly Algorithm for Optimal Tuning of PID Controller Parameters. *Proceeding IEEE of 4th International Conference on Power Engineering, Energy and Electrical Drives*, Istanbul, Turkey. 13-17 May 2013. 1293-1296.

Bevrani, H., Habibi, P., babahajyani, P. Watanabe, M., and Mitani, Y. (2012). Intelligent Frequency Control in an AC Microgrid: Online PSO-Based Fuzzy Tuning Approach. *Proceeding IEEE Transactions on Smart Grid*. December 2012. 1935-1944.

Billings, S. A., Voon, W. S. F. (1986). Correlation Based Model Validity Tests for Nonlinear Models. *International Journal of Control*. 44, 235–244.

Bisegna, P., Caruso, G. and Maceri, F. (2006). Optimized Electric Networks for Vibration Damping Of Piezoactuated Beams. *Journal of Sound and Vibration*. 289, 908-937.

Bingul, Z. and Karahan, O. (2011). A Fuzzy Logic Controller Tuned with PSO for 2 DOF Robot Trajectory Control. *Journal of Expert Systems with Applications*. 38, 1017–1031.

Blevins, R. D. (1979). *Formulas for Natural Frequency and Mode Shape*. New York: Van Nostrand Reinhold.

Bosch, P. P. J., and Klauw, A. C. (1994). *Modeling, Identification, and Simulation of Dynamical Systems*. Boca Raton: CRC Press.

Bruel and Kjaer. (2005). Brüel & Kjær Sound & Vibration Measurement A/S (Power amplifier type 2706). Naerum, Denmark.

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

Cavallo, A., De Maria, G. Natale, C. and Pirozzi, S. (2010). *Active Control of Flexible Structures from Modeling to Implementation – Chapter 2: Modelling of Flexible Structures*. Springer.

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

Chakraverty, S. (2009). Vibration of Plates. First edition Taylor & Francis Group, LLC.

Changhao, S. and Duan, H. (2013). ABC Optimized Controller for Unmanned Rotorcraft Pendulum. *An International Journal Aircraft Engineering and Aerospace Technology*, vol. 2(2), 104-114.

Chokpanyasuwan, C. pothiya, S., Anantasate, S., and Bhasaputra, P. (2009). Optimal Fuzzy Logic Controller Design using Particle Swarm Optimization for Wind-Natural Gas Power System. *6th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, Pattaya, Chonburi. 6-9 May 2009. 164-167.

Cuomo, G., Tirindelli, M. and Allsop, W. (2007). Wave in Deck Loads on Exposed Jetties. *Coastal Engineering*. 54, 657-679.

Dash, P., Saika, L. C., and Sinha, N. (2015). Automatic Generation Control of Multi Area Thermal System using Bat Algorithm Optimized PD–PID Cascade Controller. *Journal of Electrical Power and Energy Systems*. 68, 364–372.

Dash, J., Dam, B. and Swain, R. (2016). Optimal Design of Linear Phase Multi-Band Stop Filters using Improved Cuckoo Search Particle Swarm Optimization. *Journal of Applied Soft Computing*. 52, 435-445.

Dlugach, M. I. (1972). The Construction of Systems of Finite-Difference Equations for Calculations Involving Plates and Shells. *Journal International Applied Mechanics*. 8, 76-79.

Dongshan, G., Kunyi, C., yongchao, Y., Shaowu, L. and Qing, A. (2014). A Research of DC Motor Dual Close-loop PID Speed-tuning System on the Basis of ABC Algorithm. *The 26th Chinese Control and Decision Conference (CCDC),* Changsha, China. 21 May-2 Jun 2014. 3450-2454.

Dong, I. K. and Sungkwun K. (1993). An Iterative Learning Control Method with Application for CNC Machine Tools. *Proceeding IEEE of Industry Applications Society Annual Meeting*, Toronto, Ont. 2-8 October 1993. 2106-2111.

Dorigo, M. and Caro, G. D. (1999). *The Ant Colony Optimization Meta-Heuristic. In Book, New Ideas in Optimization*, pages 11–32. Mc Graw-Hill, Maidenhead, UK England.

Dounis, A. I., Kofinas, P., Alafodimos, C. and Tseles, D. (2013). Adaptive Fuzzy Gain Scheduling PID Controller for Maximum Power Point Tracking Of Photovoltaic System. *An International Journal of Renewable Energy*. 60, 202-214.

Doung, V. and Stubberud, A. (2002). System Identification by Genetic Algorithm. *Proceeding of IEEEAC on Aerospace Conference Proceedings*, CA, USA., 9-16 March 2002. 2331-2337.

Dutta, R., Ganguli, R. and Mani, V. (2011). Swarm Intelligence Algorithms for Integrated Optimization of Piezoelectric Actuator and Sensor Placement and Feedback Gains. *Smart materials and Structures*. 20(10), 105018-105032.

Ebrahimnejad, A., Tavana, M. and Alrezaamiri, H. (2016). A Novel Artificial Bee Colony Algorithm for Shortest Path Problems with Fuzzy Arc Weights. *Journal of Measurement*. 93, 48-56.

Elkhateeb, N. A. and badr, R. I. (2013). Employing Artificial Bee Colony with Dynamic Inertia Weight for Optimal Tuning of PID Controller. *Proceedings of International Conference on Modeling, Identification and Control (ICMIC)*, Cairo, Egypt. 31 August-2 September 2013. 42-46.

Elsisi, M., Soliman, M., Aboelela, M. A. S. and Mansour, W. (2016). Bat Inspired Algorithm Based Optimal Design of Model Predictive Load Frequency Control. *Journal of Electrical Power and Energy Systems*. 83, 426-433.

Engelbrecht, A. P. (2007). *Computational Intelligence*. 2nd Edition, John Wiley and Sons Ltd, University of Pretoria, South Africa.

Fadil, M. A. and Darus, I. Z. M. (2013). Evolutionary Algorithms for Self-tuning Active Vibration Control of Flexible Beam. *Proceeding IEEE Australian Control Conference*, Perth, Australia. 2-5 November 2013. 104-108.

Fang, H., Chen, L., and Shen, Z. (2011). Application of an Improved PSO Algorithm to Optimal Tuning Of PID Gains for Water Turbine Governor. *Journal of Energy Conversion and Management*. 52, 1763–1770.

Fei, G., Yibo, Q., Qiang, Y. and Jiaqing, X. (2010). An Novel Optimal PID Tuning and On–line Tuning Based on Artificial Bee Colony Algorithm. *Proceeding IEEE International Conference of Computational Intelligence and Software Engineering (CiSE)*, Wuhan, China. 10-12 dec. 2010. 1-4.

Fister, I., Jr, I. F., Yang, X. S. and Brest, J. (2013). A Comprehensive Review of Firefly Algorithms. *Swarm and Evolutionary Computation*, 13:34-46.

Gardonio, P., Bianchi, E. and Elliott, S. J. (2004a). Smart Panel with Multiple Decentralized Units for the Control of Sound Transmission. Part I: Theoretical Predictions. *Journal of Sound and Vibration*. 274, 163-192.

Gardonio, P., Bianchi, E. and Elliott, S. J. (2004b). Smart Panel with Multiple Decentralized Units for the Control of Sound Transmission. Part II: Design of the Decenteralized Control Units. *Journal of Sound and Vibration*. 274, 193-213.

Gardonio, P., Bianchi, E. and Elliott, S. J. (2004c). Smart Panel with Multiple Decentralized Units for the Control of Sound Transmission. Part III: Control System Implementation. *Journal of Sound and Vibration*. 274, 215-232.

Geng, J and Qi, L. (2005). An Open-Closed-Loop Pid-Type Iterative Learning Control Algorithm for Uncertain Time-Delay Systems. *Proceedings of the Fourth International Conference on Machine Learning and Cybernetics*, Guangzhou, China. 18-21 August 2005. 1154-1159.

Goda, Y. (1974). New Wave Pressure Formulae for Composite Breakwaters. *Coastal Engineering Proceedings*. 14, 1702-1720.

Goldfarb, M. and Sirithanapipat, T. (1999). The Effect of Actuator Saturation on the Performance of PD-Controlled Servo Systems. *Mechatronics*. 9(5), 497-511.

Gozde, H., Cengiz, M. T. and Kocaarslan, I. (2012). Comparative Performance Analysis of Artificial Bee Colony Algorithm in Automatic Generation Control for Interconnected Reheat Thermal Power System. *Journal of Electrical Power and Energy Systems*. 42, 167–178.

Gu, F., Ngai, M. K. and Quang, H. (2008). Automatic Fuzzy Membership Function Tuning using the Particle Swarm Optimisation. *Proceeding of IEEE Pacific-Asia Workshop on Computational Intelligence and Industrial Application*, Wuhan, China. 19-20 December 2008. 324-328.

GW Instek Co. (2015). Function Generator GFG-8250A. Taiwan.

Hadi, M. S., Hashim, M. H., and Darus, I. Z. M. (2012). Genetic Modeling of a Rectangular Flexible Plate System with Free-Free-Clamped-Clamped (FFCC) Edges. *Proceeding IEEE Conference on Control, Systems and Industrial Informatics (ICCSII)*. 23-26 September 2012. 173-179.

Hagood, N. W. and Flotow, A. (1991). Damping of Structural Vibrations with Piezoelectric Materials and Passive Electrical Networks. *Journal of sound and Vibration*. 14, 243-268.

Hai, M. H. (2009). Design of the Low Density Mixture Liquid Control System based on Iterative Learning Control Theory. *2nd International conference on Intelligent Computation Technology and Automation*. 10-11 October. Changsha, China. 849-851.

Hameed, I. A. (2011). Using Gaussian Membership Functions for Improving the Reliability and Robustness of Students' Evaluation Systems. *Journal of Expert Systems with Applications*. 38(6), 7135-7142.

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.

Hasancebi, O., Teke, T. and Pekcan, O. (2013). A Bat Inspired Algorithm for Structural Optimization. *Journal of Computer and Structures*. 128, 77-90.

Hengjie, L. and Xiaohong, H. (2010). A Fast PID Type Parameter Optimal Iterative Learning Control Algorithm for Non-Positive Plants. *Proceedings of the 29th Chinese Control Conference*. 29-31 July. Beijing, China. 2091-2096.

Hongbo, L. and Abraham, A. (2005). Fuzzy Adaptive Turbulent Particle Swarm Optimization. *Fifth International Conference on Hybrid Intelligent Systems (HIS)*, Rio de Janeiro, Brazil. 6-9 November 2005.

Hu, Q., Ma, G and Li, C. (2004). Active Vibration Control of a Flexible Plate Structure Using LMI-Based H∞ Output Feedback Control Law. *Proceeding of the 5th World Congress on Intelligent Control and Automation*. 15-19 June. Hangzhou, China. 738-742.

Hossain, M. A. and Tokhi, M. O. (1997). Evolutionary adaptive active vibration control. *Proc. Inst. Mech. Engrs, Part I.* 211:183 193.

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

Ismail, R., Mat Darus, I. Z. and Ismail, A. Y. (2006). Identification Algorithms of Flexible Structure using Neural Networks. *In Proceedings of 2006 4th Student Conference on Research and Development*, 27-28 June. Selangor, Malaysia, 162-168.

Jalil, N. A. and Mat Darus, I. Z. (2013). System Identification of Flexible Beam Structure using Artificial Neural Network. *Proceedings of the fifth IEEE International Conference on Computational Intelligence, Modeling and Simulation*. 24-25 September. Seoul, Korea, 3-7.

Jamid, M. F., and Mat Darus, I. Z. (2010). Development of a Flexible Plate Structure Rig for Implementation of Active Vibration Control Algorithm. *Fourth Asia International Conference on Mathematical/Analytical Modelling and Computer Simulation*. 26-28 May 2010. 610-614.

Javadi, S. and Hojjatinia, Z. (2012). Evaluation of Optimal Fuzzy Membership Function for Wind Speed Forecasting. *International Journal of Smart Electrical Engineering*. 1(2), 125-130.

Jia, P. T., and Tzuu, H. S. L. (2012). Hybrid Clonal Selection Algorithm and the Artificial Bee Colony Algorithm for a Variable PID-like Fuzzy Controller Design. *Proceedings of International Conference on Fuzzy Theory and Its Applications*. Taichung, Taiwan. 16-18 November 2012.

Jinxue, X., Qi, Z. and Xiangdong, W. (2008). A PID-IMP Type Iterative Learning Controller. *Proceedings of the 7th World Congress on Intelligent Control and Automation*, Chongqing, China. 25-27 June 2008. 785-789.

Jnifene, A. (2007). Active Vibration Control of Flexible Structures using Delayed Position Feedback. *Journal of Systems and Control Letters*. 56:215.

Juing, S. C., Shun, T. L. and Ming, T. L. (2012). A PSO-Based Adaptive Fuzzy PID-controllers. *Journal of Simulation Modelling Practice and Theory*. 26, 49-59.

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.

Julai, S., Tokhi, M. O., Mohamad, M. and Abd. Latiff, I. (2010). Active Vibration Control of a Flexible Plate Structure using Particle Swarm Optimization. *Proceeding of IEEE 9th International Conference on Cybernetic Intelligent Systems (CIS)*, Reading, United Kingdom.

Kafader, U. (2014). *Motion Control for Newbies*. Sachseln: Maxon Motor.

Kalani, H., Sardarabadi, M. and Fard, M. P. (2016). Using Artificial Neural Network Models and Particle Swarm Optimization for Manner Prediction of a Photovoltaic Thermal Nanofluid Based Collector. *Journal of Applied Thermal Engineering*. 113, 1170-1177.

Kaplan, P., Murray, J. J. and Yu, W. C. (1995). Theoretical Analysis of Wave Impact Forces on Platform deck Structures. *Offshore Mechanics and Arctic engineering Conference*, Copenhagen, 189-198.

Kar, I. N., Miyakura, T. and Seto, K. (2000). Bending and Torsional Vibration Control of a Flexible Plate Structure Using *H* -Based Robust Control Law. *IEEE Transactions on Control Systems Technology*. 8(3):545-553.

Karaboga, D. (2005). *An Idea Based on Honey Bee Swarm for Numerical Optimization*, Technical Report-TR06, Erciyes University, Engineering Faculty, Computer Engineering Department.

Karaboga, D. and Basturk, B. (2008). On The Performance of Artificial Bee Colony (ABC) Algorithm. *International Journal of Applied Soft Computing*. 8, 687-697.

Karaboga, D. and Kaya, E. (2016). An Adaptive and Hybrid Artificial Bee Colony Algorithm (aABC) for ANFIS Training. *Journal of Applied Soft Computing*. 49, 423-436.

Kaur, A and Kaur, A. (2013). Comparison of Mamdani-Type and Sugeno-Type Fuzzy Inference Systems for Air Conditioning System. *International Journal of Soft Computing and Engineering*. 2(2), 323-325.

Kennedy, J. and Eberhart, R. (1995). Particle Swarm Optimization. *Proceedings IEEE International Conference on Neural Networks*, 4:1942–1948.

Kesharaju, M. and Nagarajah, R. (2016). Particle Swarm Optimization approach to defect detection in armour ceramics. *Journal of Ultrasonics*. 75, 124-131.

Khooban, M. H., and Niknam, T. (2015). New Intelligent Online Fuzzy Tuning Approach for Multi-Area Load Frequency Control: Self Adaptive Modified Bat Algorithm. *Journal of Electrical Power and Energy Systems*. 71, 254–261.

Kistler, G. (2011). Miniature PiezoBeam Accelerometer-Light Weight IEPE TEDS Accelerometer. Winterthur, Switzerland.

Kuan, Y. C., Pi, C. T. Mong, T. T., and Yi, H. F. (2009). A Self-Tuning Fuzzy PID-Type Controller Design for Unbalance Compensation in an Active Magnetic Bearing. *Journal of Expert Systems with Applications*. 36, 8560–8570.

Leitch, R. R. and Tokhi, M. O. (1987). Active Noise Control Systems. *IEEE Proceedings A Physical Science, Measurement and Instrumentation, Managements and Education, Review*. 134, 525-546.

Li, W. P., Luo, B. and Huang, H. (2016). Active Vibration Control of Flexible Joint Manipulator using Input Shaping and Adaptive Parameter Auto Disturbance rejection Controller. *Journal of Sound and Vibration*. 363, 97-125.

Lin, C. J., Li, T. H. S., Kuo, P. H. and Wang, Y. H. (2015). Integrated particle swarm optimization algorithm based obstacle avoidance control design for home service robot. *Journal Computers and Electrical Engineering*. 56, 748-762.

Lin, T. Y. L., Yeh, J. T. and Kuo, W. S. (2016). Using Particle Swarm Optimization Algorithm to Search For a Power Ascension Path of Boiling Water Reactors. *Journal Annals of Nuclear Energy*. 102, 37-46.

Ljung, L. (1987). *System Identification: Theory for the User*, Upper Saddle River, N.J.: Prentice Hall PTR.

Loncar, G., Carevic, D. and Bekic, D. (2015). Analysis of Vertical Pressure Load Exerted on Horizontal RC Plates by Wave Impact. *Gradevinar*. 67, 985-995.

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

Ma, X., Lu, Y. and Wang, F. (2017). Active Structural Acoustic Control of Helicopter Interior Multifrequency Noise using Input-Output Based Hybrid Control. *Journal of Sound and Vibration*. 405, 187-207.

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.

Magdalene, M., Yannis, M. and Georgios, E. S. (2011). Vibration control of beams with piezoelectric sensors and actuators using particle swarm optimization. *Journal Expert Systems with Applications*. 38, 6872-6883.

Mahamood, M. R. (2012). Direct Adaptive Hybrid PD-PID Controller for Two-Link Flexible Robotic Manipulator. *Proceedings of the World Congress on Engineering and Computer Science, vol. II WCECS 2012*, October 24-26, San Francisco, USA, 1127-1132.

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.

Mann, G. K., Hu, B. G. and Gosine, R. G. (1999). Analysis of Direct Action Fuzzy PID Controller Structures. *Systems, Man, and Cybernetics*, *Part B: Cybernetics*, *IEEE Transactions on.* 29(3), 371-388.

Mat Darus, I. Z. (2004). *Soft Computing adaptive active vibration control of flexible structures*. PhD Thesis, Department of Automatic Control and Systems Engineering, University of Sheffield, UK.

Mat Darus, I. Z. and Tokhi, M.O. (2004). Parametric Modeling of a Flexible 2D Structure. *Journal of Low Frequency Noise, Vibration and Active Control*. 23(2), 115 – 131.

Mat Darus, I. Z. and Tokhi, M. O. (2004). Finite Difference Simulation of a Flexible Plate Structure. *Journal of Low Frequency Noise, Vibration and Active Control*. 23(1), 27-46.

Mat Darus, I. Z. and Tokhi, M. O. (2005). Soft computing-based active vibration control of a flexible structure. *Journal of Engineering Application of Artificial Intelligence*. 18, 95-114.

Mat Darus, I. Z. and Al-Khafaji, A. A. M. (2012). Non-parametric modeling of a rectangular flexible plate structure. *Journal Engineering Applications of Artificial Intelligence*. 25, 94-106.

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.

Massel, S. R., Oleszkiewicz, M. and Trapp, W. (1978). Impact Wave Forces on Vertical and Horizontal Plate. *Coastal Engineering Proceedings*. 16, 2340-2359.

Md Salleh, S., Tokhi, M. O., Julai, S., Mohamad, M. and Abd Latiff, I. (2009). PSO based Parametric Modeling of a Thin Plate Structure. *Proceedings of the 2009 3rd UKSim European Symposium on Computer Modeling and Simulation*. United Kingdom. 43 – 48.

Md Zain, B. A., Tokhi, M. O. and Md Salleh, S. (2009). Dynamic Modelling of a Single link Flexible Manipulator using Parametric Techniques with Genetic Algorithms. *Proceedings of 2009 Third UKSim European Symposium on Computer Modelling and Simulation*. Athens, Greece. 25-27 November. 373-378.

Meng, X. B., Gao, X. Z. Liu, Y. and Zhang, H. (2015). A Novel Bat Algorithm with Habitat Selection and Doppler Effect in Echoes for optimization. *Journal of Expert Systems with Applications*. 42, 6350-6364.

Mishra, P. K. and Dey, S. S. (1987). Discrete energy method for the analysis of cylindrical shells. *Journal of Computers & Structures*. 27, 753-762.

Mishra, S., Shaw, K. and Mishra, D. (2012). A New Meta-heuristic Bat Inspired Classification Approach for Microarray Data. *Journal of Procedia Technology*. 4, 802-806.

Ming, Y. and Xingcheng, W. (2009). Fuzzy PID Controller Using Adaptive Weighted PSO for Permanent Magnet Synchronous Motor Drives. *Second International Conference on Intelligent Computation Technology and Automation*, Changsha, Hunan. 10-11 October 2009. 736-739.

Mohamad Sofi@Aziz, A. Z. (2007). *Parametric System Identification and Active Vibration Control of Vibrational Structures Using Genetic Algorithm*. Master Thesis Department of Applied Mechanics, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia.

Mohammed, M. J. (2016). *Active Vibration Control of Vortex Induced Vibration on Segmented Cylindrical Marine Riser Model*. Ph.D. Thesis Department of Applied Mechanics, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia.

Moharama, A., El-Hosseinia, M. A., and Alia, H. A. (2015). Design of Optimal PID Controller Using Hybrid Differential Evolution and Particle Swarm Optimization with an Aging Leader and Challengers. *Journal of Applied Soft Computing*. 38, 727-737.

Mohd Yatim, H. (2016). *Evolutionary Algorithms for Active Vibration Control of Flexible Manipulator*. Ph.D. Thesis Department of Applied Mechanics, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia.

Nguyen, S. D., Nguyen, Q. H. and Choi, S. B. A Hybrid Clustering Based Fuzzy Structure for Vibration Control - Part 2: An Application to Semi-Active Vehicle Seat – Suspension System. *Journal of Mechanical Systems and Signal Processing*. 56, 288-301.

Oshaba, A. S., Ali, E. S. and Elazim, S. M. (2015). MPPT Control Design of PV System Supplied SRM using BAT Search Algorithm. *Journal of Sustainable Energy, Grids and Networks*. 2, 51–60.

Patarapanich, M. (1984). Forces and Moment on a Horizontal Plate Due to Wave Scattering. *Coastal Engineering*. 8, 279-301.

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

Pivnoka, P. (2002). Comparative Analysis of Fuzzy PI/PD/PID Controller based on Classical Control Approach. *Proceedings of the 2002 IEEE International Conference on Computational Intelligence*, Honolulu, HI. 12-17 May. 541-546.

Premkumara, K. and Manikandan, B. V. (2015). Speed Control of Brushless DC Motor using Bat Algorithm Optimized Adaptive Neuro-Fuzzy Inference System. *Journal of Applied Soft Computing*. 32, 403–419.

Qiang, G, Weijun, Z. and Chao, D. (2010). Analysis and Design of an Optimal Parameter PID Iterative Learning Control Scheme for Position Servo Control System. *Proceedings of the IEEE International Conference on Information and Automation*, Harbin, China. 20 – 23 June 2010. 1678-1683.

Ra'afat, J. S. (2007). *Enhancement of Transient Stability for Iraqi Power System by using Fuzzy-Genetic Controller*. Master Thesis, University of Technology, Baghdad, Iraq.

Rahman, T. A. Z., and Mat Darus, I. Z. (2012). Active Vibration Control using Pole Placement Method of a Flexible Plate Structure Optimised by Genetic Algorithm. *Proceeding IEEE Conference on Control, Systems and Industrial Informatics (ICCSII)*. 23-26 September 2012. 92-97.

Rajasekhar, A., Das, S. and Abraham, A. (2013). Fractional Order PID Controller Design for Speed Control of Chopper Fed DC Motor Drive using Artificial Bee Colony Algorithm. *World Congress on Nature and Biologically Inspired Computing*, 12-14 August. Fargo, USA. 259-266.

Rajasekhar, A., Jatoth, R. K. and Abraham, A. (2014). Design of Intelligent PID/Piλdμ Speed Controller for Chopper Fed DC Motor Drive using Opposition Based Artificial Bee Colony Algorithm. *Journal of Engineering Applications of Artificial Intelligence*. 29, 13–32.

Ramadan, H. S., Bendary, A. F. and Nagy, S. (2016). Particle Swarm Optimization Algorithm for Capacitor Allocation Problem in Distribution Systems with Wind Turbine Generators. *Journal of Electrical Power and Energy Systems*. 84, 143-152.

Rao, B. V. and Kumar, G. V. N. (2015). Optimal Power Flow by BAT Search Algorithm for Generation Reallocation with Unified Power Flow Controller. *Journal of Electrical Power and Energy Systems.* 68, 81-88.

Rathor, S., Acharya, D. S., Gude, S. and Mishra, P. (2011). Application of Artificial Bee Colony Optimization for Load Frequency Control. *World Congress on Information and Communication Technologies*. 11-14 December. Mumbai, India. 743-747.

Saad, M. S. (2014). *Evolutionary Optimization and Real-Time Self-Tuning Active Vibration Control of a Flexible Beam System*. Ph. D. Thesis Department of Applied Mechanics, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia.

Saad, M. S., Jamaluddin, H., Mat Darus, I. Z. and Abd Rahim, I. (2015). Experimental Study of Active Vibration Control of a Flexible Beam System using Iterative Learning Algorithm. *Key Engineering Materials*. 660, 356-360.

Sadeghi, S., Saffari, H. and Bahadormanesh, N. (2015). Optimization of a Modified Double-Turbine Kalina Cycle by using Artificial Bee Colony Algorithm. *Journal of Applied Thermal Engineering*. 91, 19-32.

Sathya, M. R. and Ansari, M. M. T. (2014). Load Frequency Control using Bat Inspired Algorithm based Dual Mode Gain Scheduling of PI Controllers for Interconnected Power System. *Journal of Electrical Power and Energy Systems*. 64, 365-374.

Savran, A. and kahraman, G. (2013). A Fuzzy Model Based Adaptive PID Controller Design for Nonlinear and Uncertain Processes. *The Journal of Automation ISA Transactions*. 53, 280–288.

Sayed, M., Gharghory, S. M. and Kamal, H. A. (2015). Gain Tuning PI Controllers for Boiler Turbine Unit Using a New Hybrid Jump PSO. *Journal of Electrical Systems and Information Technology*. *2*, 99–110.

Schedin, S., Lambourge, C. and Chaigne, J. (1999). Transient Sound Fields from Impacted Plates: Comparison between Numerical Simulations and Experiments. *Journal of Sound and Vibration*. 221, 471-490.

Selamat, N. A., Wahab, N. A. and Sahlan, S. (2013). Particle Swarm Optimization for Multivariable PID Controller Tuning. *Proceeding IEEE 9th International Colloquium on Signal Processing and Its Applications*, 8-10 Mac. Kuala Lumpur, Malaysia. 170-175.

Selim, Y. and Ecir, U. K. (2015). A New Modification Approach on Bat Algorithm for Solving Optimization Problems. *Journal of Applied Soft Computing*. 28, 259–275.

Settles, M. (2005). *An Introduction to Particle Swarm Optimization*. University of Idaho, Moscow. 1-8.

Shang, T. W., Jiann, Y. C., Yuan, C. Y., and Yea, Y. C. (2007). An Active Vibration Absorber for a Flexible Plate Boundary-Controlled By a Linear Motor. *Journal of Sound and Vibration*. 300, 250-264.

Shaheed, M. H. and Tokhi, M. O. (2002). Dynamic Modelling of a Single-Link Flexible Manipulator: Parametric and Non-Parametric Approaches. *Robotica*. 20, 93-109.

Sharma, R., Rana, K. P. S. and Kumar, V. (2014). Performance Analysis of Fractional Order Fuzzy PID Controllers Applied to a Robotic Manipulator. *Expert Systems with Applications*. 41, 4274-4289.

Shleeg, A. A. and Ellabib, I. M. (2013). Comparison of Mamdani and Sugeno Fuzzy Interference Systems for the Breast Cancer Risk. *International Journal of Computer, Information, Systems and Control Engineering*. 7(10), 695-699.

Shaharuddin, N. M. R. and Darus, I. Z. M. (2012). Active Vibration Control of Marine Riser. *Proceeding IEEE Conference on Control, Systems and Industrial Informatics (ICCSII)*. 23-26 September 2012. 114-119.

Singh, K., Vasant, P., Elamvazuthi, I. and Kannan, R. (2015). PID Tuning of Servo Motor using Bat Algorithm. *Journal of Procedia Computer Science*. 60, 1798 – 1808.

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.

Sun, D., Mills, J. K., Shan, J. and Tso, S. K. (2004). A PZT Actuator Control of a Single-link Flexible Manipulator based in Linear Velocity Feedback and Actuator Placement. *Mechatronics*. 14(4), 381-401.

Sun, H., Lus, H. and Betti, R. (2012). Identification of Structural Models using a Modified Artificial Bee Colony Algorithm. *Journal of Computers and Structures*. 116, 59-74.

Supriyono, H. and Tokhi, M. O. (2012). Parametric Modeling Approach using Bacterial Foraging Algorithms for Modeling of Flexible Manipulator Systems. *Engineering Applications of Artificial Intelligence*. 898-916.

Tavakolpour, A.R. (2010). *Mechatronic Design of an Intelligent Active Vibration Control for Flexible Structures.* Ph. D. Thesis Department of Applied Mechanics, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia.

Thida, M., Eng. H. L., Monekosso, D. N. and Remagnino, P. (2012). A Particle Swarm Optimisation Algorithm with Interactive Swarms for Tracking Multiple Target. *Journal Applied Soft Computing*. 13, 3106-3117.

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. *Journal of Mechanical Systems and Signal Processing.* 10, 667-682.

Tokhi, M. O. and Azad, A. K. M. (2008). *Flexible Robot Manipulators Modelling, Simulation and Control*. Institution of Engineering and Technology, London, United Kingdom.

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.

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

Wang, Y., Yu, Y., Zhang, G., and Sheng, X. (2012). Fuzzy Auto-adjust PID Controller Design of Brushless DC Motor. *Journal of Physics Procedia*. 33, 1533 – 1539.

Wijdeven, J. V. D., and Bosgra, O. (2007). Hankel Iterative Learning Control for Residual Vibration Suppression with MIMO Flexible Structure Experiments. *Proceedings of the 2007 American Control Conference, New York, USA.* 11-13 July 2007. 4993-4998.

Wu, J., Wang, Y., Huang, J. and Xing, K. (2012). Artificial Bee Colony Algorithm based Auto-Disturbance Rejection Control for Rehabilitation Robotic Arm Driven by PM-TS Actuator. *Proceedings of International Conference on Modelling, Identification and Control*, 24-26 June. Wuhan, China. 802-807.

Wei, D. C. and Shun, P. S. (2010). PID Controller Design of Nonlinear Systems Using an Improved Particle Swarm Optimization Approach. *Journal of Communication Nonlinear Science Numerical Simulation*. 15, 3632–3639.

Xianmin, Z., Changjian, Sh. and Erdman, A. G. (2002). Active Vibration Controller Design and Comparison Study of Flexible Linkage Mechanism Systems. *Journal of Mechanism and Machine Theory*. 37, 985-997.

Xian, B. M., Gao, X. Z., Yu, L., and Hengzhen, Z. (2015). A Novel Bat Algorithm with Habitat Selection and Doppler Effect in Echoes for Optimization. *Journal of Expert Systems with Applications*. 42, 6350–6364.

Xiaoe, R. and Zhaozen, L. (2014). Convergence Characteristics of PD-Type Iterative Learning Control Indiscrete Frequency Domain. *Journal of Process Control*. 24, 86–94.

Xu, Q., Kan, J., Chen, S. and Yan, S. (2014). Fuzzy PID Based Trajectory Tracking Control of Mobile Robot and its Simulation in Simulink. *International Journal of Control and Automation*. 7(8), 233-244.

Xufei, D., Zhili, L. and Jianguo, Z. (2015). PSO Based on Chaotic Map and Its Application to PID Controller Self-Tuning. *16th International Conference on Electronic Packaging Technology (ICEPT),* Changsha, China, 11-14 August 2015, 1470-1476.

Yang, X. S. (2010). A New Metaheuristic Bat-Inspired Algorithm, in: Gonzlez, J., Pelta, D., Cruz, C., Terrazas, G., Krasnogor N. (Eds.), Nature Inspired Cooperative Strategies for Optimization (NICSO 2010), Vol. 284 of Studies in Computational Intelligence, Springer, Berlin, Heidelberg, 2010, pp. 65–74.

Yang, X. S. (2010a). *Nature-Inspired Metaheuristic Algorithms*. Second edition, Luniver Press, United Kingdom.

Yang X. S. (2010b). A New Metaheuristic Bat-Inspired Algorithm. *Chapter, Nature Inspired Cooperative Strategies for Optimization (NICSO 2010), the series Studies in Computational Intelligence*, 284:65-74.

Yang, X. S. and Deb, S. (2009). Cuckoo Search via Levy Flights. *Proceeding of World Congress on Nature & Biologically Inspired Computing*, December. India. 210-214.

Yang, X. S. and Deb, S. (2010). Engineering Optimisation by Cuckoo Search. *International Journal of Mathematical Modelling and Numerical Optimisation*. 1(4), 330–343.

Ye, J., Hajirasouliha, I., Becque, J. and Eslami, A. (2016). Optimum Design of Cold-Formed Steel Beams using Particle Swarm Optimisation Method. *Journal of Constructional Steel Research*. 122, 80-93.

Yilmaz, S. and Kucuksille, E. U. (2014). A New Modification Approach on Bat Algorithm for Solving Optimization Problems. *Journal of Applied Soft Computing*. 28, 259-275.

Ying, C. W., Chiang, J. C. and Ching, C. T. (2003). An Adaptive PID-type Iterative Learning Controller for Nonlinear Systems with Initial State Errors. *Proceeding IEEE European Control Conference (ECC),* Cambridge, UK. 1-4 September 2003. 1507-1512.

Yiqiang, L., yaobin, C. and Huixing, Z. (2009). Control of Ironless Permanent Magnet Linear Synchronous Motor Using Fast Terminal Sliding Mode Control with Iterative Learning Control. *American Control Conference*, St. Louis, MO, USA. 10-12 June 2009. 5486-5491.

Yong, X., Tong, Z., and Guoping, C. (2013). Dynamic Modeling and Active Control of Flexible Plate Based on the Input-Output Data. *Journal of Acta Mechanica Solida Sinica*. 26 (3), 255-262.

Yu, Q. and Shanshan, D. (1997). A Fuzzy PID Controller Optimized By Genetic Algorithms Used for a Single Phase Factor Pre-Regulator. *23rd International Conference on Industrial Electronics, Control and Instrumentation (IECON),* New Orleans, LA. 9-14 November 1997. 338-342.

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

Zaeri, R., Ghanbarzadeh, A. Attaran, B. and Zaeri, Z. (2011). Fuzzy Logic Controller based Pitch Control of Aircraft tuned with Bees Algorithm. *2nd International Conference on Control, Instrumentation and Automation (ICCIA),* Shiraz, Iran. 27-29 December 2011. 1217-1221.

Zaher, H., Kandil, A. E. aand Fahmy, R. (2014) Comparison of Mamdani and Sugeno Fuzzy Inference Systems for Prediction (With Application to Prices of Fund in Egypt). *British Journal of Mathematics and Computer Science*. 4(21), 3014-3022.

Zakaria, M. Z., Saad, M. S., Jamaluddin, H. and Ahmad, R. (2014). Dynamic System Modeling of Flexible Beam System using Multi-Objective Optimization Differential Evolution Algorithm. *Applied Mechanics and Materials*. 695, 605-608.

Zamani, M., Ghartemani, M. K., Sadati, N., and Parniani, M. (2009). Design of a Fractional Order PID Controller for an AVR Using Particle Swarm Optimization. *Journal of Control Engineering Practice*. 17, 1380–1387.

Zhang, Y., Zhao, Y., Fu, X. and Xu, J. (2016). A Feature Extraction Method of the Particle Swarm Optimization Algorithm Based on Adaptive Inertia Weight and Chaos Optimization for Brillouin Scattering Spectra. *Journal Optics Communications*. 376, 56-66.

Zhi, C. Q., Hong, X. W., and Chun, D. Y. (2009). Acceleration Sensors Based Modal Identification and Active Vibration Control Of Flexible Smart Cantilever Plate. *Journal of Aerospace Science and Technology*. 13, 277-290.

Zhi, W. Y., Ming, W. W., Wei, L., and Shao, B. C. (2015). Fuzzy Entropy Based Optimal Thresholding using Bat Algorithm. *Journal of Applied Soft Computing*. 31, 381–395.

Zhenhua, Z., Yinghui, Z. and Shanshan, L. (2009). Algorithm Research of Fuzzy-PID Parameters Self-tuning Wall Thickness Controller. *Proceedings of IEEE International Conference on Mechatronics and Automation*, Changchun, China. 9 – 12 August 2009. 428-432.

Zhong, F., Li, H. and Zhong, S. (2016). An Improved Artificial Bee Colony Algorithm with Modified-Neighborhood based Update Operator and Independent-Inheriting-Search Strategy for Global Optimization. *Journal Engineering Applications of Artificial Intelligence*. 58, 134-156.