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

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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.

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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^t_{mean}	-	The average loudness of all bats
$a_{1\ldots}a_n\ b_1\ldots b_n$	-	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
v	-	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

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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.

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