INTELLIGENT IDENTIFICATION AND CONTROL OF A FLEXIBLE BEAM

MOHD AZIMIN BIN ELIAS

A thesis submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Engineering (Mechanical)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

JUNE 2016

To Allah

To my father, my wife and my lovely children

ACKNOWLEDGEMENT

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

First of all, I would like to express my gratitude to Allah for His blessings bestowed and His perfect plan, I am able to prepare this thesis accordingly. Secondly, many people have come into my path in preparing the thesis and have contributed to the success of the thesis. In particular, I wish to express my sincere appreciation to my supervisor, Assoc. Prof. Dr. Intan Zaurah binti Mat Darus whose guidance, critics and support, has made the completion of the thesis possible.

Appreciation also goes to my family for their continuous support, who have been patient with my family time spent for the thesis. My fellow postgraduate colleagues are as well appreciated who have provided assistance in various occasions.

Last but not least, I would like to extend my appreciation to Universiti Teknologi Malaysia (UTM) for the facilities provided in completing this thesis.

ABSTRACT

High demands in weight reduction have been observed in many areas. There are many benefits with weight reduction including reducing cost, increase efficiency and pushing the technology beyond the limit. The weight reduction requires lighter materials to be used, therefore less stiff structures are utilized. The less stiff the structure, the more flexible and easier it is to vibrate. The vibration produced by these types of structures may cause a lot of problems, including fatigue failure, resonance failure, defects, and even life. This project studies a type of structure configuration; a flexible cantilever beam. The objectives of this project are to identify the model and to develop the controller for the flexible beam. Previous studies have shown various methods are suitable to identify the system, these include the ones considered in this project; the parametric modelling using Recursive Least Square, as well as the non-parametric modelling using Multilayer Perceptron Neural Network. An experimental rig of flexible cantilever beam is developed for this project to obtain the input data for the system identification. A Proportional-Integral-Derivative controller is developed utilizing both system models identified, using automatic and heuristic tunings techniques within MATLAB environment. The performance developed by the controller is verified through simulations in MATLAB Simulink. The controller is proven to be stable with significant vibration suppression of the flexible beam.

ABSTRAK

Pengurangan berat di dalam pelbagai bidang telah menjadi permintaan yang tinggi mutakahir ini. Terdapat perlbagai manfaat jika berat sesuatu objek dapat dikurangkan. Ini termasuklah mengurangkan kos, mengingkatkan kecekapan proses dan meneroka melebihi batas-batas teknologi. Pengurangan berat memerlukan bahan yang lebih ringan untuk digunakan, oleh itu, bahan yang kurang keras digunakan. Kurangnya keras sesuatu bahan itu, maka bahan itu lebih anjal dan lebih mudah untuk bergetar. Getaran ini boleh menyebabkan pelbagai masalah, seperti kelelahan bahan, kegagalan resonan, kerosakan bahan, malah boleh membahayakan nyawa. Projek ini mengkaji salah satu jenis konfigurasi struktur, iaitu bim anjal terjulur. Objektif projek ini adalah untuk mengenalpasti model dan membina pengawal untuk mengawal getaran bim ini. Kajian-kajian terdahulu telah menunjukkan pelbagai kaedah telah digunakan untuk mengenalpasti model getaran bim, ini termasuklah kaedah yang digunakan di dalam projek ini iaitu kaedah parametric dengan Recursive Least Square dan juga kaeda bukan parametric dengan Multilayer Perceptron Neural Network. Sebuah ujikaji telah dijalankan ke atas bim anjal di dalam sebuah eksperimen untuk mendapatkan data di dalam mengenalpasti system tersebut. Pengawal Proportional-Integral-Derivative telah dibina menggunakan kedua-dua model yang telah dikenalpasti menggunakan dua kaedah pengenalpasti, menggunakan teknik automatik dan heuristik di dalam persekitaran MATLAB. Prestasi pengawal disahkan di dalam simulasi MATLAB Simulink. Pengawal ini terbukti berkesan berdasarkan pengurangan getaran yang signifikan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1. Background

The need of lighter materials for a lot of applications has increased nowadays. This need will soon multiplied in the future. The applications that are taking advantages of lighter materials range across almost every engineering verticals; automotive, aerospace, civil, marine, manufacturing, bio-medical and a lot more.

These engineering verticals utilize and rely heavily on beams. Car body structure, for example, is mainly constructed by beams. Aircraft wings are having main structure called spar, being a classic example for a flexible cantilevered beam. On the other hand, a lot of component holders for both automotive and aerospace applications are of beam-like structures.

Beam is also present as the main material especially for steel structures in the civil industry. Beam also dominantly being the main structure in the form of concrete in the civil industry. Similarly, off-shore structures are predominantly constructed from steel beams. While machineries that are utilized for civil constructions, for example the excavators, the diggers, the cranes; their moving parts are having beams as part of their structures. This can also be seen in underwater remotely-operated vehicles (ROV) with robotic manipulators; the moving parts, i.e. the manipulators, are mainly beam-like structures. Similar manipulators are also present in the aerospace industry, where outer-space robotic arms are handy in assisting the astronauts.

In the manufacturing lines, robotic arms utilization has been increased the automation in the production, therefore increasing the production, as well as decreasing the man hours required. These robotic arms are beams. Similar types of beam-like robotic arms are also present in the bio-medical line, where these arms have assisted doctors and medical specialists in numerous complicated and high-accuracy surgeries. These beam-like structures indeed have assisted in saving lives.

Table 1.1 describes the advantages and the disadvantage of beam, especially as part of any structure.

Table 1.1 : Advantages and disadvantage of flexible beam

Advantages	**Disadvantages**
Does not require support on the opposite side	Large deflections
Reach large span	Less adept at carrying torsion

With the important applications across various engineering verticals, lighter materials, or lighter beam specifically, will indeed assist in increasing the efficiency of the applications. Nevertheless, lighter beam means this will reduce the stiffness of the beam. Through physics, the flexibility concept describes that the less stiffness, the structure becomes more flexible. Through physics still, the modal concept explains that the less stiffness, the easier the structure vibrates.

Excessive vibrations will cause other problems. These problems include:

- Fatigue on structures
- Prone to resonance
- Manufacturing defects
- Maintenance error
- Medical error that may cause loss of lives

These problems have then increased the need of vibration suppression on flexible beam to avoid such problems. Recently, it has become paramount for researchers in designing effective control methods that suppress the vibration of flexible beam.

1.2. Objectives

The objectives of the thesis are as follows:

1. To model a flexible beam system subjected to vibration using system identification techniques.

2. To design, simulate and validate PID controllers using several tuning methods for vibration suppression of flexible beam structure.

1.3. Problem Statement

The need to weight reduction of a structure has contributed to low stiffness of it that will increase the ability of the structure to vibrate. Vibrations on the other hand, will increase other structural failure, including fatigue. A controller will allow the vibration of the structure to be suppressed, therefore, decrease the possibility of structural failure.

However, to represent a system of vibrating beam to be integrated in the controller is complex, which is by solving the equation of motion in a second order partial differential equation. A system identification method simplifies the system representation of a vibrating beam.

1.4. Scope

The thesis shall cover the following:

1. The study covers the vibration of a thin cantilevered beam.
2. An experiment is conducted to obtain input and output data for system identification of the structure.
3. A parametric method utilizing Recursive Least Square (RLS) is used to identify the system in comparison to a non-parametric method using Multi-Layer Perceptron Neural Network (MLP-NN).
4. PID controller is tuned using automatic tuning and heuristic tuning methods for vibration suppression of the flexible beam structure.
5. Thus developed controller is validated within simulation environment only.

1.5. Theoretical Framework

The thesis consists heavily of the engineering areas of system identification and control. The key theories that are touched in the thesis are RLS system identification and PID controller. The non-parametric method for system identification; the neural network, is another key theory that is heavily discussed in the thesis.

Nevertheless, the equation of motion that describes the vibration of a beam, is a second order partial differential equation, as shown in Equation 1.1.

$$\frac{\delta^2}{\delta x^2}\left[EI(x)\frac{\delta^2 w(x,t)}{\delta x^2}\right] + \rho A(x)\frac{\delta^2 w(x,t)}{\delta t^2} = f(x,t) \qquad (1.1)$$

It is empirical that this equation is difficult to be solved for a vibrating flexible beam. Hence the decision to utilize system identification to estimate the parametric equation that describes the response of a vibrating flexible beam.

REFERENCES

Akira Abe and Kotaro Hashimoto (2015). A Novel Feedforward Control Technique for a Flexible Dual Manipulator. *Robotics and Computer-Integrated Manufacturing*. 35, 169-177.

Ali Reza Tavakolpour, Musa Mailah, Intan Z Mat Darus and Osman Tokhi (2010). Self-Learning Active Vibration Control of a Flexible Plate Structure with Piezoelectric Actuator *Simulation Modelling Practice and Theory*. 18, 516-532.

Ashokpandiyan N., Mythiliraj A. and Rajkumar P. (2014). Reducing the Vibration on Wing by Using Piezoelectric Actuator. *Journal of Aeronautical and Automotive Engineering (JAAE)*. 1, 13-16.

Barun Pratiher (2012). Vibration Control of a Transversely Excited Cantilever Beam with Tip Mass. *Archive of Applied Mechanics*. 82 (1): 31-42.

Bao Rong, Xiao-Ting Rui and Ling Tao (2012). Dynamics and Genetic Fuzzy Neural Network Vibration Control Design of a Smart Flexible Four-Bar Linkage Mechanism. *Multibody System Dynamics*. 28 (4), 291-311.

Boucetta R and Abdelkrim M. A. (2012). Neural Network Modeling of a Flexible Manipulator Robot. *International Federation for Information Processing*. 395-404.

Carr, D. M. (1986), PID Control and Controller Tuning Techniques, Eurotherms's PID control. 1, 1-11. Eurotherm Controls Inc.

Christian Dullinger, Alexander Schirrer and Martin Kozek (2015). Data-based and Analytic Modelling for Model-Based Control of a Flexible Beam. *IFAC-PapersOnline*. 48 (1), 73-74.

Dafang W., Liang H., Bing P., Yuewu W. and Shang W. (2014). Experimental Study and Numerical Simulation of Active Vibration Control of a Highly Flexible Beam Using Piezoelectric Intelligent Material. *Aerospace Science and Technology*. 37, 10-19.

Dubay R., Hassan M., Li C. and Charest M. (2014). Finite Element Based Model Predictive Control for Active Vibration Suppression of a One-Link Flexible Manipulator. *ISA Transactions.* 53, 1609-1619.

Dunant Halim, Xi Luo and Pavel M Trivailo (2014). Decentralized Vibration Control of a Multi-Link Flexible Robotic Manipulator Using Smart Piezoelectric Transducers *Acta Astronautica*. 104, 186-196.

Fadil M A, Jalil, N.A. and Mat Darus, I.Z. (2013). Intelligent PID Controller Using Iterative Learning Algorithm for Active Vibration Controller of Flexible Beam. *IEEE Symposium on Computers and Informatics ISCI 2013*. 7-9 April 2013. Langkawi, Malaysia: 80-85.

Ganjefar S., Rezaei S. and Pourseifi M. (2015). Self-Adaptive Vibration Control of Simply Supported Beam Under a Moving Mass Using Self-Recurrent Wavelet Neural Networks via Adaptive Learning Rates. *Meccanica*. 50 (12), 2879-2898.

Hadi M S and Mat Darus I Z. (2013). Intelligence Swarm Model Optimization of Flexible Plate Structure System. *International Review of Automatic Control.* 6 (3), 322-331.

Jalil N A and Mat Darus I.Z. (2013). Non-Parametric Neuro-Model of A Flexible Beam Structure. *IEEE Symposium on Computers and Informatics ISCI 2013*. 7-9 April 2013. Langkawi, Malaysia: 45-50.

Jalil N A and Mat Darus I.Z. (2012). Neuro-Fuzzy Identification of Flexible Beam Structure. *1st IEEE Conference on Control, Systems and Industrial Informatics, ICCSII 2012.* 23-26 September 2012. Bandung, Indonesia: 185-190.

Jalil N A and Mat Darus I.Z. (2014). Neuro Identification for Flexible Cantilever Beam Structure. *International Review on Modelling and Simulations*. 7 (2), 341-349.

Jing-jun Wei, Zhi-cheng Qiu, Jian-da Han and Yue-chao Wang (2010). Experimental Comparison Research on Active Vibration Control for Flexible Piezoelectric Manipulator Using Fuzzy Controller. *Journal of Intelligent Robotic Systems: Theory and Applications*. 59 (1), 31-56.

Kelly Cohen, Tanchum Weller and Joseph Z Ben-Asher (2012) Active Control of Flexible Structures Using a Fuzzy Logic Algorithm. *Smart Materials and Structures*. 11, 541-552.

Khoshnood A. M. and Moradi H. M. (2014). Robust Adaptive Vibration Control of a Flexible Structure. *ISA Transactions*. 53, 1253-1260.

Landau, I. D., Lozano, R., M'Saad, M. and Karimi, A. (2011). Adaptive Control Algorithms, Analysis and Applications. (2nd ed.). New York: Springer.

Mat Darus I. Z. and Tokhi M. O. (2005). Soft Computing-Based Active Vibration Control of a Flexible Structure. *Engineering Application of Artificial Intelligence*. 18, 93-114.

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

Mikles, J. and Fikar, M. (2007). Process Modelling, Identification, and Control. (1st ed.). New York: Springer.

Nestorovic T., Durrani N. and Trajkov M. (2012). Experimental Model Identification and Vibration Control of a Smart Cantilever Beam Using Piezoelectric Actuators and Sensors. *Journal of Electroceramics*. 29 (1), 42-55.

Nili Ahmadabadi Z. and Khadem S.E. (2014). Nonlinear Vibration Control and Energy Harvesting of a Beam Using a Nonlinear Energy Sink and a Piezoelectric Device. *Journal of Sound and Vibration*. 333, 4444-4457.

Nima S. Mahmoodi, Mehdi Ahmadian and Daniel J. Inman (2010). Adaptive Modified Positive Position Feedback for Active Vibration Control of Structures. *Journal of Intelligent Material Systems and Structures*. 21, 571-579.

Nise, N. S. (2011). Control Systems Engineering. (6th ed.). New Jersey: John Wiley & Sons, Inc.

Saad M. S., Jamaluddin H. and Mat Darus I. Z. (2015). Online Monitoring and Self-Tuning Control Using Pole Placement Method for Active Vibration Control of a Flexible Beam. *Journal of Vibration and Control.* 21 (3), 449-460.

Salleh S. M. and Tokhi M. O. (2009). Active Vibration Control of a Flexible Plate Using Recursive Least Square with Directional Forgetting Factor. *16th International Congress on Sound and Vibration 2009, ICSV 2009.* 5-9 July 2009. Krakow, Poland: 5, 3120-3127.

Shungqi Z., Schimdt R. and Xiansheng Q. (2015). Active vibration control of piezoelectric bonded smart structures using PID algorithm. *Chinese Journal of Aeronautics*. 28(1), 305-313.

Suzuki Y. and Kagawa Y. (2010). Active Vibration Control of a Flexible Cantilever Beam Using Shape Memory Alloy Actuators. *Smart Materials and Structures.* 19 (8), 9.

Velthius W. J. R., de Vries T. J. A and van Amerongen J. (1996). Learning feed forward control of a flexible beam. *Proceedings of the 1996 IEEE International Symposium on Intelligent Control*. Dearborn, MI: 2:30.

Wang H., Shen G., Li L. and Zhong X. (2015). Study on the Maglev Vehicle-Guideway Coupling Vibration System. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit.* 229 (5), 507-517.

Wang H., Shen G. and Zhou J. (2014). Control Strategy of Maglev Vehicles Based on Particle Swarm Algorithm. *Journal of Modern Transportation*. 22 (1), 30-36.

Wu S. T., Lian S. H. and Chen S. H. (2015). Vibration Control of a Flexible Beam Driven by a Ball-Screw Stage with Adaptive Notch Filters and a Line Enhancer. *Journal of Sound and Vibration.* 348, 71-87.

Yatim H.M. and Mat Darus I.Z. (2014). Intelligent Parametric Identification of Flexible Manipulator System. *International Review of Mechanical Engineering.* 8 (1), 11-21.

Zhang T., Li H. G. and Cai G. P. (2013). Hysteresis Identification and Adaptive Vibration Control for a Smart Cantilever Beam by a Piezoelectric Actuator. *Sensors and Actuators.* 203, 168-175.

Zhicheng Qiu, Xiangtong Zhang and Chunde Ye (2012). Vibration Suppression of a Flexible Piezoelectric Beam Using BP Neural Network Controller. *Acta Mechanica Solida Sinica*. 25, 417-428.

Zhou Z., Huo R. and Zhang X. (2011). Research on Active Vibration Control of Piezoelectric Intelligent Beam Based on Energy Finite Element Method. *Electrical*, *Information Entineering and Mechatronics*. 138, 1627-1635.