DEVELOPMENT OF A SEMI-ACTIVE BYPASS VISCOUS DAMPER FOR BRIDGE STRUCTURES SUBJECTED TO DYNAMIC LOADS

By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

September 2021

FK 2021 115

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Variable traffic vibration loads on overcrossing and bridges are the cause of damages in essential load-bearing components could consequently lead to damage or failure of the bridge. Nowadays, the fluid viscous dampers are the most conventional energy dissipation system to implement in bridges. However, the viscous dampers are the passive type control system and its function is the same for an entire operation time of the device. Since the applied vibration in the bridge is dependent on various traffic loads (heavy, medium, and low traffic), it is required to change the function of the damper.

In this research, a Semi-active Bypass Viscous Damper is developed by utilizing a pair of external fluid flow patches as bypass valves to the sides of the viscous damper cylinder to flow the fluid from two chambers of the cylinder during the movement of the piston. Two flow control valves have been implemented in the device to control the flow pressure of the fluid passing through the bypass valve during the functioning of the damper device. Therefore, the function of the damper device is adjustable by changing the flow control valves positions within a range upon the displacement of the structure.

The analytical model of the proposed bypass viscous damper is developed and the performance of the device under different loading conditions has been formulated according to the control valves position and fluid pressure inside the cylinder. Then the finite volume model of the moving fluid inside the device has been developed and the function of the device evaluated through Computational Fluid Dynamics (CFD) analysis.

In the next step, the prototype of the damper and the control panel has been fabricated and synchronized to perform the real-time control of the damper. Then the experimental tests have been conducted using a dynamic actuator.

The numerical analysis and experimental test results for the prototype revealed that the developed device is capable of developing a wide range of damping levels and there is a desirable agreement between numerical predictions and experimental results.

Thereafter, in order to examine the effect of the application of the semi-active control system in the bridge structures, the proposed system was implemented in the 19/5 California overcrossing bridge. The considered bridge equipped with the damper device is modeled using the finite element method and it is subjected to the passing vehicle loadings. The results showed that the bridge's response is dramatically improved with the implementation of the developed damper systems by reducing the peak displacement of the structure up to 70 percent by the mean of the semi-active control system while the control valves have been set to be 50 percent of the operational level of the device.

Afterward, to develop a real-time control system, a Fuzzy control algorithm has been developed and implemented to the numerical model. The fuzzy control algorithm is designed based on the formulated performance and it is introduced according to the American AASHTO standard code for minimum, maximum allowable, and extreme traffic loads applying to the bridge.

Then, to enhance the function of the semi-active system in a real-time control system, a MATLAB Simulink code was developed, and the control system with a semi-active Fuzzy control loop was implemented in a 3-story concrete frame structure subjected to a seismic load. The resultant data from this numerical study revealed that the developed semi-active Fuzzy control system works effectively to control the maximum displacement of the structure under seismic loads. Although the number and location of the installed dampers are very important and should be designed properly to obtain the desirable displacement control.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN PENYERAP LIKAT PINTASAN SEPARUH AKTIF UNTUK STRUKTUR JAMBATAN YANG TERTAKLUK KEPADA BEBAN DINAMIK

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Beban getaran lalu lintas yang berubah-ubah diatas lintasan dan jambatan adalah punca keletihan dan kerosakan pada komponen galas beban penting seperti galas getah akan menyebabkan kerosakam atau kegagalan jambatan tersebut. Pada masa kini, penyerap likat bendalir adalah sistem pelepasan tenaga yang paling konvensional untuk diaplikasikan di jambatan. Walau bagaimanaapun, penyerap likat adalah sistem kawalan jenis pasif dan ianya berfungsi sama untuk kesuluruhan masa operasi peranti. Memandangkan, getaran yang digunakan di jambatan bergantung pada pelbagai beban lalu lintas (lalu lintas berat, sederhana, dan rendah), ianya perlu menukar fungsi penyerap. Dalam penyelidikan ini, Penyerap Likat Pintas Separuh Aktif dimajukan dengan menggunakan sepasang tompok aliran bendalir luaran sebagai injap pintasan ke sisi silinder penyerap likat untuk mengalirkan bendalir daripada dua ruang silinder semasa pergerakan omboh. Dua injap kawalan aliran telah diaplikasikan didalam peranti untuk mengawal tekanan aliran bendalir yang melalui injap pintasan semasa penyerap peranti itu berfungsi. Oleh itu, fungsi peranti boleh dilaraskan dengan menukar kedudukan injap kawalan aliran dalam julat anjakan struktur yang ditetapkan.

Model analitikal peranti yang dicadangkan dimajukan dan prestasi peranti tersebut dalam keadaan pemuatan yang berbeza telah dirumuskan mengikut kedudukan kawalan injap dan tekanan bendalir di dalam silinder. Selepas itu, model volum terhingga bendalir bergerak di dalam peranti telah dimajukan dan fungsi peranti dinilai melalui analisis Dinamik Bendalir Pengiraan (CFD).

Dalam langkah seterusnya, prototaip peranti dan panel kawalan telah direka dan disegerakkan untuk melaksanakan kawalan masa nyata penyerap tersebut. Selepas itu, ujian eksperimen dilakukan menggunakan penggerak dinamik.

Analisis berangka dan keputusan ujian eksperimen untuk prototaip mendedahkan bahawa peranti yang dimajukan mampu membangunkan pelbagai tahap penyerap dan terdapat persetujuaan yang wajar diantara ramalan berangka dan keputusan eksperimen.

Oleh yang demikian, untuk mengkaji kesan penggunaan peranti didalam stuktur jambatan, peranti yang dicadangkan diaplikasikan di lintasan jambatan 19/5. Jambatan yang dipertimbangkan telah dilengkapi dengan peranti yang dimodelkan menggunakan kaedah elemen terhingga dan ianya tertakluk kepada muatan kenderaan yang lalu. Keputusan menunjukkan bahawa tindak balas jambatan bertambah baik secara mendadak dengan pelaksanaan sistem penyerap yang dimajukan dengan mengurangkan anjakan puncak struktur sebanyak kira-kira 70 peratus dengan purata min enam penyerap manakala injap kawalan telah ditetapkan kepada 50 peratus daripada tahap operasi peranti.

Selepas itu, untuk memajukan sistem kawalan masa nyata, algoritma kawalan Fuzzy telah dimajukan dan diaplikasikan kepada model berangka. Algoritma kawalan Fuzzy telah direka bentuk berdasarkan prestasi yang dirumuskan dan telah diperkenalkan mengikut kod standard AASHTO Amerika untuk kod minimum, maksimum yang dibenarkan dan lalu lintas beban yang melampau yang dikenakan pada jambatan.

Kemudian, untuk meningkatkan fungsi separa aktif dalam sistem kawalan masa nyata, kod MATLAB Simulink telah dimajukan, dan peranti dengan gelung kawalan Fuzzy separa aktif telah diaplikasikan dalam struktur rangka konkrit 3 tingkat yang telah dikenakan beban seismik. Data terhasil daripada kajian berangka mendedahkan bahawa sistem kawalan Fuzzy separa aktif yang dimajukan berfungsi dengan berkesan untuk mengawal anjakan maksimum struktur di bawah beban seismik. Walaupun bilangan dan lokasi peranti yang dipasang adalah sangat penting dan harus direka bentuk dengan betul untuk mendapatkan kawalan anjakan yang diingini.

ACKNOWLEDGEMENTS

Foremost, I would like to express my sincere gratitude to my advisor Prof. Farzad Hejazi for the continuous support of my Ph.D. study and research, and for his patience, motivation, enthusiasm, and immense knowledge.

Besides my advisor, I would like to thank the rest of my thesis committee: Prof. Mohd Saleh bin Jaafar, and Prof. Faizal bin Mustapha for their encouragement, insightful comments, and hard questions.

My sincere thanks also go to the University of Putra Malaysia and Hercules Engineering, for offering me the facilities, equipment, and opportunities in their groups and leading me to work on diverse exciting projects.

I thank my classmates in the Anti-vibration group for the stimulating discussions, for the all experiences and work we have done together, and for all the fun we have had in the last four years.

I would like to thank all my friends who always push me further and my leaders who always inspire and encourage me.

And last but not least, I would like to thank my family:

My mother, Badri Feiz, my father, Dr. Mehdi Farahpour, and my charming and intelligent son, Mohammad Hossein Kelich, who had faith in me and sacrificed a lot for me.

My brothers and sisters, Hoda, Neda, Hamed, and Habib who always had believe in my strengths even when I felt weak.

And Nafas and Artin who brought a wave of energy and freshness to the last four years.

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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LIST OF ABBREVIATIONS

A_{cl}	Cylinder Cross Section Area
A_{pp}	Cross-Section Area Of The Pipe
A_{Shaft}	Occupied Cross Section Area By Shaft
C	Damping Coefficient
D_{pp}	Pipe Internal Diameter
f	Friction Factor
F_D	Control Force
$F_{Damping}$	Damping Force
g	Gravitational Acceleration
h_L	Total Flow Head Loss
h_{major}	Major Head Loss
h_{minor}	Minor Head Loss
K	Stiffness
K_1	Loss Coefficient
K_L	Head Loss Coefficient
L_{pp}	Pipe Length
M	Mass Flow
n	Current Time Level
n+1	Next Time Level
p	Pressure
P_{ED}	Maximum Internal Pressure
P_{RD}	Maximum Allowable Pressure
S_ϕ	Source Term Of Φ

t	Time
v	Fluid Velocity
v_{pp}	Flow Velocity Inside The Pipe
x	Displacement
u	Mesh Velocity
β	Closing Position Of The Valves In Percentage
ρ	Fluid Density
Γ	Diffusion Coefficient

CHAPTER 1

INTRODUCTION

1.1 Introduction

Most of the time, highway over crossings, bridges, and building damage are the result of underestimating excessive seismic displacements and the large dynamic forces applied to the structure during their life spans. On the other hand, conclusive evidence shows highway bridges are routinely subjected to larger than anticipated vehicle loads that may shorten the useful service life of these vital structures. Given the abundance of bridge failures, many research programs were conducted to improve the dynamic behavior of structures. With the help of strong-motion records, enhancements have been achieved in the design, analysis, and also retrofit programs of bridge structures.

Although provisions for bridge failure have been defined in the design procedure (Xiang et al., 2019) but still the development of more reliable techniques is required. The increasing need for safer bridges has led to the implementation of various control techniques including passive, active, and semi-active methods to mitigate structural sway in bridges and buildings. Since passive systems have fixed performance and the outcome resultant force is not adjusted according to the required response of the structure, active and semi-active control systems as a practical possibility for vibration control mostly have been considered.

Active control of the bridge structure by using a control surface system with winglets was presented by Phan (2020) which helps a long suspension bridge reach a stable state of flutter and buffeting.

Semi-active control systems are a class of active control systems that use the motion of the structure to develop the control forces and the required external energy is smaller amounts in comparison with the active control method. Battery power can be sufficient to make a semi-active system operative for real-time control.

Recently, the automotive semi-active suspension (SAS) system with the nonlinear hydraulic adjustable damper has been used in automobiles (Ma et al., 2019). The concept of the application of a semi-active control to bridges was described by Peng et al. (2022). They discussed the possibility of outfitting bridges with semi-active dampers to provide vibration control.

Table 1.1 : Restrainer systems, methods and the research gap

Restrainer System	Methods	Research Gap
Stiffness-Based Restrainer	Tie-plate Steel Restrainer, Concrete Shear Keys, High Resistance Steel Cables, FRP Cables	Residual Displacement, Additional Stiffness, No Energy Dissipation.
Self-Centring Restrainer	SMA devices, Pre-load Spring Damper, pre-tensioned tendons and energy dissipators, steel dual-core prestressed tensioning members, viscous damper with imposed preloads.	Costly, Temperature Dependency, Frequent Maintenance, Complex design and Manufacturing, Low Energy Dissipation.
Passive Vibration Energy Dissipation Restrainers	Metallic Dampers (Straight and tapered Steel Rods, X-shape, Triangular, U and E Steel Plates, Steel Pipes, Tunned Liquid Dampers, Viscoelastic Dampers, Fluid Viscous Damper, Viscous Wall Dampers,	limited Energy Dissipation Capacity, Not adjustable with Changing of Dynamic Forces, Not Accurate Vibration Control.
Active Vibration Energy Dissipation System	Quadratic Regulator System, Closed Hydraulic System	Large External Power Source, Actuator's Failure, Additional Energy
Semi-active Control Systems	MR, ER, Pisoelectricity friction Dampers	Very Expensive Technology, Sensitive to Temperature Variations

According to the interaction between vehicle, loads, and the structure, the control methods can be categorized into three main categories, stiffness-based restrainers, energy dissipation restrainers, and self-centering restrainers.

These restrainer systems with particular methods and the research gaps that may limit a wider implementation of these restrainers in bridge structures have been listed in Table 1-1. In between, passive fluid viscous dampers as an energy dissipation restrainer method, when properly specified and designed, have served as a structure's primary defense to prevent catastrophic damage and costly repairs.

The successfulness of the control system quite depends on the primary design of the factors and parameters of the whole system, not only the device itself but also the configuration of the hydraulic circuit, control algorithm, and also time delay considerations.

However, seismic activities are highly doubtful concerning scale and nature, the semi-active fluid viscous damper is capable of developing a wide range of damping levels between design upper and lower bound. So that the decrease in the structural reaction will be promising and obtained through transferring some of the structural shaking energy to supplementary dampers added to the main building.

1.2 Statement of the problem

Nowadays, the fluid viscous dampers are the most conventional energy dissipation system which is implemented in the bridges to prevent any excessive movements on the structure due to traffic loads. However, the vibration on the bridge structure depends on the traffic load which is variable and continually changes, therefore, it is required to adopt the function of the damper device according to the applied excitation to effectively protect the bridges against frequent and severer vibrations. Hence, to adjust the function of viscous dampers according to the required response of the structure, two different systems have been developed recently, "variable damping" and "variable stiffness" semi-active viscous damper devices. For the first category, the device is designed so that the damping characteristics are adjustable during the operation, whereas in the second group, only the stiffness of the device changes. However, these developed semi-active systems, are not able to meet all the precise control requirements for the research gaps listed as follow:

- Semi-Active Variable Stiffness System: this system has been examined with On-off Operation within the configuration of the lock mechanism of one bracing system. The developed system applied a small change in Stiffness and provided a limited control band. (Kobori, 1999)
- Semi-Active Variable Damping System: this device has been developed by using a bypass hydraulic system with the on-off operation, and LRQ and COC control algorithm, the performance is stable for a specific range of velocity amplitude of the excitation. Time delay, costly hydraulic circuit, and maximum 4 valve positions limited the device function. (Oliveira and Morais, 2012).

Hence, this study proposes a new semi-active variable stiffness and damping control system to control the vibration behavior of the bridge structure while subjected to changing traffic loads.

This control system consists of a fluid damper, a programmable logic controller (PLC), pressure transmitters, and displacement sensors. The proposed Semi-Active control system consists of a hydraulic cylinder with a pair of external bypass pipes with motorized electric flow control valves which are installed in the middle of pipes to control the flow rate of the fluid from one chamber of the hydraulic cylinder to another. A programmable logic controller (PLC) is implemented to manage the operation of both motorized valves according to the movement of the bridge which is measured through displacement sensors.

Therefore, the pressure inside the hydraulic cylinder is controllable and the function of the device is adaptive so that the integrated control system can perform a real-time control during its operation.

This damper device is mainly originated from a passive fluid viscous damper and dissipates energy on the principle of head loss phenomena caused by fluid resistance while flowing through different sections. The damper adjusts the proper damping and stiffness, simultaneously, within a range, without shifting the ratio of the natural frequency of the structure. The device is low-cost and low-maintenance and is able to absorb a relatively high level of energy throughout the excitation event. This semi-active control damper can operate and provide real-time control during different conditions.

1.3 Objectives of the study

The proposed vibration control system will be used to mitigate the vibration energy caused by vehicular traffic, wind, earthquake, and other dynamic excitations. The emphasis of the work is proposing a new technique for the reduction of the vibration, through the development of a synchronized hardware and software system that can be added to the design of a new structure or retrofitted to existing ones to extend their service life. Thus, specific objectives that contribute to this aim include:

1) To develop a new semi-active variable stiffness and damping control system consisting of a fluid Damper, a programmable logic controller (PLC), pressure transmitters, and displacement sensors to control bridge structures subjected to traffic loads.
2) To develop a finite volume model to measure the fluid characteristics, pressure, and velocity, inside the damper device and simulate the resultant force as an output performance and optimize the design of the device components.
3) To validate the numerical results, through manufacturing the lab-size prototype and conducting the experimental tests using the dynamic actuator.
4) To minimize the displacement response of the deck of the bridge structure due to traffic loads by developing a control algorithm.

1.4 Hypothesis

Implementing the semi-active vibration dissipation system able to dissipate bridge vibration effectively to protect the bridge structure since it is adopting its own performance according to the applied vibrations through the smart controller.

1.5 Scope and limitation of work

To ensure that the above objectives are achieved, the present study is organized as follow:

1) To develop the finite element model of the bridge-damper, the Newton Raphson method, along with implicit numerical integration methods were utilized to provide a solution of the nonlinear system. The analysis has been done using the commercial software ANSYS 2019 R1. To define the dynamic and structural parameters of the damper the Maxwell model has been used through implementing spring elements by assuming that the properties can be represented by a spring and a dashpot connected in series.
2) To analyze the bridge, the traffic load conditions have been considered according to The American Association of State Highway and Transportation Officials standards (AASHTO,1996).
3) The fabrication process of the proposed devices is established based on the availability of materials, simplicity of manufacturing, and university test equipment capacity.
4) The geometry, boundary condition, and material specifications of the device have been defined according to the design of the prototype for testing by using a hydraulic jack.
5) According to the limitation of the test equipment, the maximum excitation force has been considered to be equal to 300 kN. A horizontal electro-hydraulic actuator was used to implement a saw-tooth displacement pattern. To evaluate the damper device accurately, three or more cycles of loading were applied at a predefined condition (JSSI Manual, 2003).
6) For analytical prediction and experimental testing, the temperature is set to 30 degrees Celsius, which is the same as the ambient temperature. However, to maintain the desired temperature during the experimental test, sufficient rest time has been considered in between each cycle test to avoid any temperature rise.
7) The prototype for the control system has been fabricated according to the ISO9002 industry-standard procedures to offer quality assurance.

1.6 Organization of Dissertation

A brief narrative of the remaining chapters is presented as follow:

Chapter 2 provides a background review and current status on the development of different bridge restrainer methods including passive, semi-active, and active control systems. Different materials and configurations for innovative semi-active fluid dampers are presented to demonstrate a thorough understanding of the existing knowledge in this field.

Chapter 3 presents the research methodology of the current study, including the initial design of the device, hydraulic circuit, and control algorithm. Then the whole procedure of the parametric study, finite element simulations, and numerical analysis was discussed. Moreover, the process of fabrication of prototypes and experimental test setups is also introduced.

Chapter 4 extensively reports the initial assessment results and the numerical and experimental evaluation of the Viscous Bypass Damper under dynamic loading.

Chapter 5 summarizes the present study and provides its general and specific conclusions. The scope of future works and recommendations are also discussed.

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