



**ADAPTIVE CONTROL SYSTEMS FOR STRUCTURES SUBJECTED TO
EARTHQUAKE AND WIND LOADINGS**

By

ABDULATEEF WISAM SAFAA ABDULATEEF

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

November 2023

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November 2023

Chairman : Prof. Raizal Saifulnaz Bin Muhammad Rashid, PhD
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Current vibration dissipation systems are inadequate for effectively managing varying load patterns and structural responses to excitations. A robust vibration control system capable of handling multidirectional structural response interactions is crucial, particularly in controlling both story drift and acceleration, as improving one can often exacerbate the other. Traditional model-based control algorithms have limited adaptivity due to their reliance on explicitly defined structural properties and the need for extensive training data, making them less adaptable to unpredictable excitations.

This research addresses these challenges in two parts. In Part One, a Fuzzy Logic Multi-Verse Optimal Control (FLMVOC) system is developed as a new adaptive real-time vibration control mechanism for structures subjected to seismic and wind loads. This system integrates a stochastic optimization method with fuzzy logic techniques, employing a magnetorheological damper (MR) as a controllable vibration damping system. The fuzzy logic controller (FLC) utilizes story drift and absolute acceleration as inputs and outputs the MR commanding voltage. The FLC is trained using the multi-objective multi-verse algorithm (MOMVO) within a hybrid MATLAB-Simulink and finite element simulation framework to optimize the controller parameters. The FLMVOC system is tested on both seismic-excited structures and high-rise buildings subjected to wind loads, demonstrating its effectiveness in reducing dynamic structural responses. In Part Two, an Online Fuzzy Logic Multi-Verse Optimal Vibration Control system (Online-FLMVOC) is developed to address the problem of system dependency on training data. This novel system combines fuzzy logic inference with the multi-verse optimization algorithm and introduces a decentralized approach with memory-saving mechanisms. The Online-FLMVOC is evaluated on a three-story shear building subjected to seismic loads and a 76-story benchmark building facing multidirectional wind loads, showcasing its real-time adaptability and effectiveness in minimizing structural responses.

Results show that the FLMVOC system reduced structural drifts by 60%, 53%, and 41% during the El Centro, Kobe, and Northridge earthquakes, respectively, with corresponding reductions in floor absolute acceleration of 38%, 17%, and 10%. In wind-induced structures, the system kept floor acceleration within comfort criteria while reducing story drift. The Online-FLMVOC system further improved performance, reducing structural drifts by 75% and 48% during the El Centro and Northridge earthquakes, with reductions in floor absolute acceleration of 60% and 26%, respectively. For wind-induced responses, the system achieved reductions in story displacement by 37.5%, 14.5%, and 12% for across wind, along wind, and rotational responses, respectively. The Online-FLMVOC system achieved similar control effectiveness to reference algorithms but with only 45% to 66% of the required control force. In conclusion, the developed FLMVOC and Online-FLMVOC systems successfully address the challenges outlined, offering competitive performance against other vibration control strategies under varying load patterns. However, further investigation is needed to assess the reliability of these adaptive vibration control systems on real-prototype structures.

Keywords: Adaptive structures, Fuzzy logic, Multi verse, Online optimization, Vibration control system

SDG: GOAL 13: Adaptive buildings, Sustainable cities, GOAL 12: Responsible consumption.

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

SISTEM KAWALAN ADAPTIF UNTUK STRUKTUR YANG TERDEKAR KEPADA BEBAN GEMPA BUMI DAN ANGIN

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Sistem pelepasan getaran semasa adalah tidak mencukupi untuk menguruskan corak beban yang berbeza-beza dan tindak balas struktur secara berkesan terhadap pengujian. Sistem kawalan getaran yang teguh yang mampu mengendalikan interaksi tindak balas struktur berbilang arah adalah penting, terutamanya dalam mengawal kedua-dua hanyut dan pecutan cerita, kerana penambahbaikan yang satu selalunya boleh memburukkan yang lain. Algoritma kawalan berasaskan model tradisional mempunyai penyesuaian yang terhad kerana pergantungan mereka pada sifat struktur yang ditakrifkan secara eksplisit dan keperluan untuk data latihan yang meluas, menjadikannya kurang menyesuaikan diri dengan pengujian yang tidak dapat diramalkan.

Penyelidikan ini menangani cabaran ini dalam dua bahagian. Dalam Bahagian Satu, sistem Kawalan Optimum Pelbagai Ayat Logik Fuzzy (FLMVOC) dibangunkan sebagai mekanisme kawalan getaran masa nyata adaptif baharu untuk struktur yang tertakluk kepada beban seismik dan angin. Sistem ini menyepadukan kaedah pengoptimuman stokastik dengan teknik logik kabur, menggunakan peredam magnetorheologi (MR) sebagai sistem redaman getaran yang boleh dikawal. Pengawal logik kabur (FLC) menggunakan hanyut cerita dan pecutan mutlak sebagai input dan output voltan arahan MR. FLC dilatih menggunakan algoritma berbilang ayat berbilang objektif (MOMVO) dalam rangka kerja simulasi MATLAB-Simulink dan unsur sehingga hibrid untuk mengoptimumkan parameter pengawal. Sistem FLMVOC diuji pada kedua-dua struktur teruja seismik dan bangunan bertingkat tinggi yang tertakluk kepada beban angin, menunjukkan keberkesanannya dalam mengurangkan tindak balas struktur dinamik. Dalam Bahagian Kedua, sistem Kawalan Getaran Optimum Berbilang Ayat Logik Kabur Dalam Talian (Online-FLMVOC) dibangunkan untuk menangani masalah pergantungan sistem pada data latihan. Sistem novel ini menggabungkan inferens logik kabur dengan algoritma pengoptimuman berbilang ayat dan memperkenalkan pendekatan terpecar dengan mekanisme penjimatan memori.

Online-FLMVOC dinilai pada bangunan ricih tiga tingkat yang tertakluk kepada beban seismik dan bangunan penanda aras 76 tingkat yang menghadapi beban angin berbilang arah, mempamerkan kebolehsuaian masa nyata dan keberkesanannya dalam meminimumkan tindak balas struktur.

Keputusan menunjukkan bahawa sistem FLMVOC mengurangkan hanyut struktur sebanyak 60%, 53%, dan 41% semasa gempa bumi El Centro, Kobe, dan Northridge, dengan pengurangan yang sepadan dalam pecutan mutlak lantai sebanyak 38%, 17% dan 10%. Dalam struktur yang disebabkan oleh angin, sistem mengekalkan pecutan lantai dalam kriteria keselesaan sambil mengurangkan hanyut cerita. Sistem Online-FLMVOC meningkatkan lagi prestasi, mengurangkan hanyut struktur sebanyak 75% dan 48% semasa gempa bumi El Centro dan Northridge, dengan pengurangan dalam pecutan mutlak lantai masing-masing sebanyak 60% dan 26%. Untuk tindak balas yang disebabkan oleh angin, sistem mencapai pengurangan dalam anjakan cerita sebanyak 37.5%, 14.5% dan 12% untuk tindak balas merentas angin, sepanjang angin dan putaran. Sistem Online-FLMVOC mencapai keberkesanan kawalan yang serupa dengan algoritma rujukan tetapi dengan hanya 45% hingga 66% daripada daya kawalan yang diperlukan. Kesimpulannya, sistem FLMVOC dan Online-FLMVOC yang dibangunkan berjaya menangani cabaran yang digariskan, menawarkan prestasi kompetitif terhadap strategi kawalan getaran lain di bawah corak beban yang berbeza-beza. Walau bagaimanapun, siasatan lanjut diperlukan untuk menilai kebolehpercayaan sistem kawalan getaran adaptif ini pada struktur prototaip sebenar.

Kata kunci: Struktur penyesuaian, Logik kabur, Berbilang ayat, Pengoptimuman dalam talian, Sistem kawalan getaran

SDG: MATLAMAT 13: Bangunan mudah suai, Bandar mampan, MATLAMAT 12: Penggunaan yang bertanggungjawab.

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LIST OF ABBREVIATIONS

v	Commanded Voltage by The Current Driver
η	Time Constant of The First Order Filter Expression For u'
lb_j	Lower Bound for The J^{th} Parameter
ub_j	Upper Bound for The J^{th} Parameter
α	MR Fluid Yield Stress
a	Acceleration Vector
A	State Space Matrix
α_a	Preload Value of MR Fluid Yield Stress
α_b	Coefficient of MR Fluid Yield Stress Variation with Respect to Command Voltage
ABC	Artificial Bee Colonies
$acc_i(t)$	The Absolute Acceleration of the i^{th} Story At Time t
ACO	Ant Colony Optimization
A_f	Floor Area
AMD	Active Mass Damper
AMTMD	Active Multiple Tuned Mass Dampers
ANN	Artificial Neural Network
ASCE	American Society of Civil Engineers
ATMD	Active Tuned Mass Damper
B	State Space Matrix for Control Force
b	Gust Factor
Bouc-Wen model	A Mathematical Model Used to Describe The Behavior Of Hysteresis In Systems Such As MR Dampers
c	In MVO: A Constant Value That Should Be More Than 1
C	Damping Matrix
C	State Space Matrix for Measured Output
c_a	Preload Value Of c_0
c_b	Coefficient Of c_0 Variation with Respect To Command Voltage
c_1	Viscous Damping Constant of The MR Damper
c_{1a}	Preload Value Of c_1
c_{1b}	Coefficient Of C_1 Variation with Respect To Command Voltage
c_0	Viscous Damping Observed at Larger Velocities
CAARC	Commonwealth Accommodation and Administration Centre
CFD	Computational Fluid Dynamics
CO	LQR-Clipped Optimal Control Strategy
C_p	Pressure Coefficients
CRIAC	Inter-University Research Centre on Building

	Aerodynamics)
C_x	Damping Coefficient Matrix
D	State Space Matrix for Measured Output
d^{max}	Maximum Uncontrolled RMS Drift
d^{max}	Maximum Uncontrolled Drift
$d_i(t)$	Story Drift at Time T For i^{th} Story
DIC	Department Of Civil Engineering
drift $_i(t)$	The Inter Story Drift of The i^{th} Story At Time t
dt	Time Step
E	State Space Matrix for Ground Acceleration
ER	Electro-Rheological
ESO	Extended-State Observer
ETABS	Extended Three-Dimensional Analysis Of Building Systems.
ETC	Electrically Tunable Capacitor
f	Total Force Generated By The MR Damper
f_1, f_2	The Proposed Objective Functions
FEM	Finite Element Method
FIS	Fuzzy Logic Inference System
FISMemory	Fuzzy Logic Inference System Memory.
FLC	Fuzzy Logic Controller
FLMVOC	Fuzzy Logic Multi-Verse Optimal Control
FLOC	Fuzzy Logic Optimal Control
FSD	Frictional Slip Damper
FSP	Friction Pendulum System
g	Acceleration Due To Gravity (9.81 m/s^2)
GA	Genetic Algorithm
GSA	Global Search Algorithm
h	Story Height
h_i	Height Of The i^{th} Story
H_2/H_∞	H_2/H Infinity Control Algorithms
HR-DAD	High Rise Database Assisted Design
HV	High Voltage
i	Story Number
J_1	Index 1 For Evaluating Algorithm Performance
J_2	Index 2 For Evaluating Algorithm Performance
J_3	Index 3 For Evaluating Algorithm Performance
J_4	Index 4 For Evaluating Algorithm Performance
J_5	Index 5 For Evaluating Algorithm Performance
J_6	Index 6 For Evaluating Algorithm Performance
JMA	Japanese Meteorological Agency

K	Stiffness Matrix
K_p, K_d	Proportional And Derivative Gains Of The Control Algorithm
k_o	Stiffness At Large Velocities
k_1	Fictitious Stiffness Due To The Accumulator
kg	Kilogram
l	Current Iteration
L	Maximum Iterations
LMI	Linear Matrix Inequalities
LMS	Least Mean Square
LN	Large Negative (Defined Fuzzy Logic Rule)
LP	Large Positive (Defined Fuzzy Logic Rule)
LP	Large Positive (Defined Fuzzy Logic Rule)
LQG	Linear Quadratic Gaussian
LQR	Linear Quadratic Regulator
LTl	Linear Time Invariant
LV	Low Voltage (Defined Fuzzy Logic Rule)
m	The Number of Earthquake or Load Components
M	Mass Matrix
MATLAB	Matrix Laboratory
max	Maximum Value of WEP
MBB	Modified quasi Bang-Bang Control Strategy
MDOF	Multi-Degree of Freedom
MeV	Medium Voltage (Defined Fuzzy Logic Rule)
min	Minimum Value of WEP
MOMVO	Multi-Objective Multi-Verse Optimization
MR	Magnetorheological
MRF	Magnetorheological Fluid
MRI	Maximum Return Interval
MR-TLCD	Magneto-Rheological Tuned Liquid Column Damper
MV	Maximum Voltage (Defined Fuzzy Logic Rule)
MV	Maximum Voltage (Defined Fuzzy Logic Rule)
MVO	Multi-Verse Optimization.
N	Negative (Defined Fuzzy Logic Rule)
n	Exponent of The Hysteresis Loop
n	The Number of Stories In A Building
N	Number of Time Steps
n	Number of Degrees of Freedom
N	Newton
N_i	The Number of Solutions Around the I^{th} Solution
NFL	No Free Lunch Theory

N-S	North-South
NSGA-II	Non-Dominated Sorted Genetic Algorithm II
NV	Neutral Voltage (Defined Fuzzy Logic Rule)
Online-FLMVOC	Online Fuzzy Logic-Based Multi-Verse Optimum Real-Time Vibration Control Algorithm
P	Positive (Defined Fuzzy Logic Rule)
p	Exploitation/Local Search Accuracy
p(t)	Control Force Vector
p _i	The Probability of Selecting The i th Solution
p _i '	The Probability of Removing The i th Solution From The Archive
PGA	Peak Ground Acceleration
PNN	Probabilistic Neural Network
PSO	Particle Swarm Optimization
PTMD	Passive Tuned Mass Damper
PZT	Piezoelectric Transducer
r ₂ , r ₃ , r ₄	Random Numbers In [0,1] Interval
RMS	Root Mean Square
s	Second
SA	Semi-Active
SA	Simulated Annealing
SAIVD-TMD	Semi-Active Variable Stiffness Tuned Mass Damper
SATMD	Semi-Active Tuned Mass Damper
SAVS	Semi-Active Variable Stiffness
SCWNN	Self-Constructing Wavelet Neural Network
SD	Standard Deviation
SDC/EEL	Structural Dynamics and Control/Earthquake Engineering Laboratory
SDOF	Single Degree of Freedom
SMC	Sliding Mode Control
SN	Small Negative (Defined Fuzzy Logic Rule)
SP	Small Positive (Defined Fuzzy Logic Rule)
t	Time
T	Period
TDR	Travelling Distance Ratio Coefficient
TMD	Tuned Mass Damper
u	Parameter Reflecting the Dynamics Involved In The MR Fluid Reaching The Rheological Equilibrium And In Driving The Electromagnet In The MR Damper
u	Displacement Vector
U	Design Mean Wind Speed at Top Floor
$\dot{u}$	Time Derivative of u

u^{max}	Maximum Uncontrolled RMS Displacement
$\ddot{u}^{max}$	Maximum Uncontrolled Absolute Floor Acceleration
$\ddot{u}_i(t)$	Relative Floor Acceleration of The i^{th} Story
u^{max}	Maximum Uncontrolled Displacement
$u_i(t)$	Horizontal Displacement of The i^{th} Story
U_r	Reference Hourly Mean Wind Speed
v	Velocity Vector
V	Basic Wind Speed
VSD	Variable Stiffness Damper
WEP	Wormhole Existence Probability Coefficient
WNN	Wavelet Neural Network
x	Absolute Displacement of The Damper Piston
$x(t)$	Ground Motion Input Vector
X_i^j	J^{th} Parameter for The i^{th} Universe
X^j	J^{th} Parameter of The Best Universe
y	Absolute Displacement of The Damper Cylinder
$\dot{y}$	Velocity of the Damper Cylinder
$y(t)$	Response Vector
Z	Zero (Defined Fuzzy Logic Rule)
z	Relative Displacement Between the Damper Piston And Cylinder
Z	Effective Structure Height
α	Power Law Exponent of Mean Wind Speed Profile
Γ	Location Matrix for Dampers
γ, β, A	Coefficients Related to The Hysteresis Behavior Of The MR Damper
λ	Penalty Constant
ρ	Air Mass Density
ψ	Inequality Function Returning 0 When the Constraint Is Confirmed And 1 When The Constraint Is Violated

CHAPTER 1

INTRODUCTION

1.1 Background

The studies on active controllers of structure response to dynamic loads showed that active controller scheme in which the forces are applied externally is not applicable to civil structures as it requires very large power sources, as a result, focus was shifted to other control systems, particularly semi-active controllers [1]. In contrast to active control, semi-active control device is one which cannot add energy in to controlled structure, instead, its properties can be changed to optimally mitigate structure response to excitation [2].

In semi-active systems, structural response can be controlled by one or multiple of the following dampers: orifice-controlled dampers (in which orifice valve utilized to alter the resistance to the flow of conventional fluid viscous damper), semi-active variable stiffness devices (SAVS), tunable liquid dampers, controllable fluids dampers (which includes electro-rheological dampers (ER), and magneto-rheological dampers (MR)) [3]. Semi-active control system over performs other control types (i.e. active and passive control systems) by combine their features and provide a viable means to protect civil structures, because of their mechanical simplicity, low required energy (as it can operate on battery power) and efficient force capacity, they constitutes as more reliable than active control system [4].

Despite of real-time response of the adaptive controller, its performance in controlling structural response mainly depends on the control algorithm. There are more than one classification for adaptive control algorithms, traditionally, it classified into two categories: model-based algorithms (LQR and LQG, are common examples) and non-model-based algorithms (such as fuzzy logic and genetic algorithms). Model-based algorithms operate on the premise of defining specific control parameters. This approach proves advantageous when monitoring variations in control parameters is essential. Conversely, non-model-based algorithms diverge from offering a direct physical interpretation of system behavior. However, they excel in efficiently addressing the inherent nonlinearity and uncertainty within the system [5]. As one of intelligent controls viable to handle uncertainties and nonlinear behavior in both environmental loads and structural properties, Fuzzy logic controllers were utilized by many researchers through unification with other control and optimization methods (especially neuro based FLC) to improve its performance [39][41][63][92]. In neuro-fuzzy control systems, two approaches are followed, direct and indirect adaptive control scheme, in the former, the dynamics of the system are not known, the controller is directly estimated and the control inputs are generated to insure stability of the system, in the latter, however, the dynamics of the system are firstly defined then a control inputs are generated according to the certainty equivalence principle [93]. It revealed from the previous studies the limited capability of model-based algorithms in

carrying the uncertainties in external excitations and structural properties since its parameters depend on the available data utilized at deriving phase. Although intelligent controllers such as fuzzy logic-based controllers are more robust (the system can withstand uncertainties in external load and structural properties) than model-based controllers, their performance depends on offline training data, i.e., despite the real-time response of the control system, the controller's parameters are not changed in real-time [38].

It is proven by previous studies that the drift and acceleration are in conflict with each other, the improvement in one may cause worse in other [6]. Developing one control strategy which capable to balance between the two effects can add advance in solving this problem, also, it would be a reliable in structural control design where both damage prevention and occupancy comfort are suggested as a design criterion. Although several researches introduced concepts for adaptive structures in high-rise buildings, these concepts involve manipulating the structure's adaptivity by applying a unit actuation load then their approach had not evaluated under the effect of dynamic load [54]. Moreover, their methodologies did not account for the effects of multidimensional and multidirectional wind loads [53].

A new vibration control system that is adaptive in nature has been proposed to overcome the drawbacks of existing model-based systems. The proposed system uses a fuzzy logic inference system as a non-model-based controller. To achieve the optimum fuzzy inference system, an integration between the inference system and a multi-objective optimization algorithm has also been proposed. The optimization is performed in real-time to ensure full adaptivity of the system. To assess the system's performance, an integrated simulation environment has been proposed, which allows for a full degree of freedom in structural analysis under the effect of a multi-component dynamic load. This will be accomplished using MATLAB, its SIMULINK toolbox, and finite element package software.

1.2 Problems Description

1. The limited capability of the traditional vibration dissipation systems to withstand the uncertainties in external load patterns and the varying structural behavior that results from such excitations.
2. The robustness of the available semi-active vibration control systems to withstand multi-component and multidirectional structure response interaction are also not well investigated.
3. The conflict action of story drift and story acceleration, the improvement in one might cause worse in the other, makes developing an adaptive control system capable of controlling both of them is crucial.

4. The limited adaptivity of model-based control algorithms (such as LQR and LQG-based algorithms) in terms of reliability and robustness since their formulation is basing on explicit definition of the structural properties.
5. The dependency of developing adaptive control algorithms on the available training data set limits its adaptability against unpredictable excitations.

1.3 Research Objectives

The overarching goal of this research is to develop a new applicable, robust, and easy control methodology for semi-active controllers in civil engineering structures subjected to the dynamic loads.

This would be achieved through the following objectives:

- i. Develop a Multi Objective Multi Verse Optimal Control (FLMVOC) system through the integration of the Fuzzy Inference technique and Multi Verse Optimization (MVO) algorithm to real-time control of structure response using semi-active Magnetorheological damper (MR) devices. Subsequently, evaluate the performance of the developed real-time structural control system to alleviate structural displacement and acceleration responses by comparing it with other available methods. This evaluation will be conducted by applying the system to a three-story shear building equipped with MR semi-active dampers subjected to seismic excitation.
- ii. Assess the robustness of the developed real-time control system to control the displacement and acceleration responses for structures under multi load components, including three components of wind load (along wind, across wind and rotational) applied to a high-rise building equipped with MR dampers.
- iii. Develop an online version of FLMVOC capable of acquiring a real-time optimal Fuzzy Logic Controller without the need for a pretraining process. Then evaluate its performance by applying the developed algorithm to a reference three-story earthquake-excited structure and a numerical wind-sensitive 76-story high-rise building subjected to three dimensional loadings.

1.4 Scope of Work

In this study, the development of new real-time vibration control system for building structures furnished with semi-active damper devices under the effect of earthquakes and wind load will be done. The developed systems will be assessed by utilizing far-field and near-field earthquake records and multidimensional wind loads to address the abovementioned problems. For comparison and validation of simulation methods purposes, only a one-dimensional structural system would be utilized in the first evaluation phase. Then a full 3D structural system of a high-rise building would be

employed under the effect of multidimensional wind load. In this study, the optimum number and distribution of the dampers are not intended. The application of the developed structural vibration control systems on a prototype or large scale structure will not be covered. However, the numerical simulation of real benchmark structures will be conducted.

Although evaluation for the proposed algorithms will be conducted on study structures by comparing results with other control algorithms, developing mathematical control law is not intended in this work. Scaling, deriving and other calculation for wind tunnel tests and earthquakes time history loads is not intended in this research. However, all data are intensively studied, and the related modelling assumptions and the use limitations would be well reviewed in the literature before applying it in this work. Designing of structural elements is not lie in the scope of this study.

1.5 Dissertation Layout

The rest of this dissertation consists of five chapters as described below:

- Chapter 2: Introduce the related literature review, highlighting the most concerned findings and the recent research trends accordingly.
- Chapter 3: Presents the followed methodology for developing the new structural vibration control systems. This chapter consists of two main sections: the development of the Fuzzy Logic Multi-Verse Optimal vibration control system (FLMVOC) and the development of a real-time optimal vibration control system (Online-FLMVOC). The evaluation of each developed system is also presented.
- Chapter 4: In this chapter, the simulation results are discussed by comparing them with the reference uncontrolled structural system and the related semi-active vibration control system from the literature. Then a conclusion was drawn accordingly.
- Chapter 5: Summarize the outcomes of the study, the performance of the developed vibration control systems and the recommended future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The concept of adaptive structure belongs to ancient ages, many monuments structures around the world which represents a simple application of adaptive technology, for instance, the steam-activated mechanism to open doors in ancient Egyptian temples (300 B.C) [7].

A smart or adaptive structure is defined as a structure which can sense its dynamic loading environment and change its response in real time, in other words, an adaptive structure is a smart machine that can change and adapt to its environment dynamically [8]. Utku [9] stated that "Adaptive structures are created by the active design paradigm where disturbances are rendered harmless not by overdesign but by adaptive means that need to take place concurrently with the disturbances".

According to existing of actuators or not, adaptive structures fall in two categories, active structures, and semi-active structures. In active structures, the system consists of sensors, actuators and microcontrollers, an external power supplies energy to control actuators which applies force(s) to the structure in predefined procedure, these forces may increase or dissipate energy from the structure [10]. By the mean of sensors, structural excitation can be measured, a feedback control searching for the desired response, and actuators generates the appropriate internal force to compensate for the forces by excitation stimulators, and minimize vibration of structure [11]. Over last twenty decades, the most active controller devices used in structural response mitigation were in forms of: active mass dampers (AMD), active tuned mass dampers (ATMD), active cables and tendons, active struts [12][13].

Studies on active controllers of structure response to dynamic loads showed that active controller scheme in which the forces are applied externally is not applicable to civil structures as it requires very large power sources, as a result, focus was shifted to other control systems, particularly semi-active controllers [1]. In contrast to active control, semi-active control device is one which cannot add energy in to controlled structure, instead, its properties can be changed to optimally mitigate structure response to excitation [2].

In semi-active systems, structural response can be controlled by one or multiple of the following dampers: orifice-controlled dampers (in which orifice valve utilized to alter the resistance to the flow of conventional fluid viscous damper), semi-active variable stiffness devices (SAVS), tunable liquid dampers, controllable fluids dampers (which

includes electro-rheological dampers (ER), and magneto-rheological dampers (MR)) Figure 2.1[3]. Semi-active control system over performs other control types (Active and passive Control systems) by combine their features and provide a viable means to protect civil structures, because of their mechanical simplicity, low required energy (as it can operate on battery power) and efficient force capacity, they constitutes as more reliable than active control system [4].

This chapter tends to present a review for concept of adaptive structures in terms of control devices, control algorithms and optimization algorithms manipulated by research during last two decades to test the performance of various control systems which are utilized to achieve desired designs and solutions for structural engineering problems.

2.2 Adaptive Structures

The use of structural controllers in civil structures offered promising alternatives for traditional design methods to alleviate undesirable response of structures to external excitation and hazards like earth-quakes and winds [14]. Various types of devices and methodologies used by researchers to examine the capability and performance of such approaches to achieve intended objectives, in following sections a review of related researches and its finding are presented.

2.2.1 Active Controllers

Active tuned mass dampers were ones of active controllers used in adaptive/smart structures. Since the proposal of passive tuned mass damper (PTMD) by Frahm in 1909, it drew attention of researches in civil engineering who applied this approach in mass researches and real world buildings [15]. Damping effect of PTMD depends on delay of structure response by 90° degree, nevertheless, this effect does not happening without tuning the PTMD frequency to the natural frequency of the structure and excitation consists of this frequency [16].

Aforementioned limitation of the use of PTMD drove researchers to develop new approaches for use of TMD. Active tuned mass damper (ATMD) was one of the earliest approaches to active control systems, it based on applying a precomputed force(s) by actuator(s) placed between the structure and the TMD [8].

Ricciardelli et al. [17] investigated the performance of passive ,active and hybrid mass dampers for mitigation of the buffeting response of tall buildings, they used two models, the first was a simple (1+1) DOF structure system equipped with mass dampers and subjected to a white noise excitation, the latter was a model of first four longitudinal modes for 64-storey building excited by more realistic buffeting force, the results are compared with a closed form design procedure from the literature, it showed

that the performance of active mass damper is bounded by the large forces and power required in real life applications.

Chunxiang et al. [18] proposed an approach of using active multiple tuned mass dampers (AMTMD) distributed uniformly in order to attenuate structural dynamic response under the effect of ground motion. Performance of the proposed system evaluated according to criterion parameters included frequency spacing, average damping ratio, tuning frequency ratio, total number, total mass ratio, and normalized acceleration feedback gain coefficient. The results showed that the performance of AMTMD increased with the increase of both the normalized acceleration feedback gain coefficient and total mass ratio, however, every ATMD in the AMTMD had different maximum stroke displacement, each of them larger than of a single ATMD.

Aly et al. [19] compared the performance of TMD and ATMD equipped in a study building of 48 storey under the effect of wind load (both across-wind and along-wind), wind loads obtained from wind tunnel test for a rigid model (scaled 1:100) with two configuration of surrounding, FEM model of the building was carried out with 3 DoF, lateral response (x and y direction) were controlled by two ATMD (one for each direction), while the torsional response recorded instantaneously by adding it to lateral response. They concluded that both TMD and ATMD has a good performance in reduction of building response, however, because of the effect of vortex shedding along the thinner direction, the controllers are less effective in terms of lateral and torsional response in one direction than the other which led to selection of bigger mass for TMD and higher control force for ATMD.

In order to overcome the structural complexity and system of uncertainties of a cable-stayed structure bridges subjected to earthquake excitations, active tendons and decentralized neurocontroller approach had been utilized by Xu et al. [20]. Their study conducted by computational simulation of six-cable-stayed bridge model, using neural network algorithm to train each neurocontroller, then evaluation of the approach for dynamic response control and damage detection was carried out, they concluded that trained neurocontrollers for original state of structure are not applicable for damage detection, on-line training through the life cycle of the structure was proposed as a solution for this issue. However, they also stated that proposed approach is adaptive and very useful for large-scale or complex structural systems when actuators with sufficient capability are available.

Adam and Smith [21] adapted a multi objective algorithm using pareto filtering and hierarchical selection to increase robustness of control commands for active struts in active tensegrity structure, they tested a full scale active tensegrity structure under 24 load cases, their results showed that multi objective based control system is more efficient for various load cases than single objective control system, nevertheless, it provides more global understanding of tensegrity structure behaviour.

Ferreira and Simões [22] proposed a multi objective optimization algorithm for cable-stayed footbridge furnished with active (they used one active tendon) and passive (passive damper) controllers. Using stress, cost, acceleration and displacement as objectives functions, two structures were numerically modelled and tested (passive and active controller's-based structure), optimization results compared with LQR based controller and showed that proposed algorithm over performs LQR for the two cases.

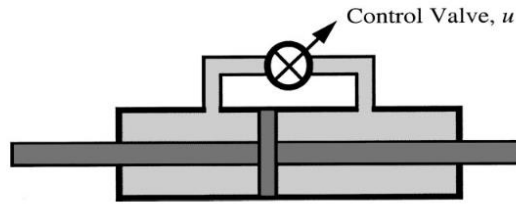
Although many studies had conducted and proposed various strategies to control building response by active controllers, effectively mitigating of vibration is costly for tall buildings in terms of energy consumption, this was main reason behind focusing on semi-active control devices as an alternative of active controllers [23].

2.2.2 Semi-active Controllers

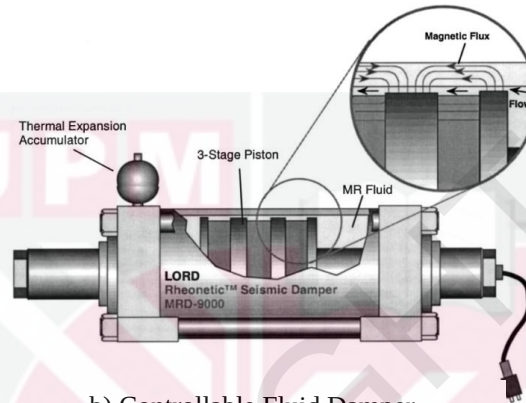
Large amount of forces are required by actuators in fully active control systems, these requirements are increasing and become pragmatically challenging in tall buildings with the increase of height, especially when various vibration loads are expected such as wind load. Conversely, semi-active controllers are not required high forces actuators nor high energy consumption and it safe when control failure happen as it simply, a controllable passive device. In semi-active controllers, energy is required only to adjust dampers properties and hence batteries are mostly used to supply required energy. In this subsection a review of studies for using semi-active vibration control systems for structures under earthquake and/or wind load excitation are presented.

Semi-Active devices categorized in four types: variable-orifice dampers, variable-stiffness device, controllable-fluid dampers, and variable-friction dampers, Figure 2.1. Nagarajaiah and Varadarajan. [24] evaluated the effectiveness of semi-active variable stiffness tuned mass damper (SAIVD-TMD) to mitigate structural response of 76-storey slender concrete building (benchmark building locating in Melbourne, Australia) subjected to wind load, they used empirical mode decomposition (EMD) technique and Hilbert transform algorithm (HB) (developed by the writers) to tune frequencies of (SAIVD-TMD), taking in accounts the uncertainties of stiffness to evaluate robustness of controller, fundamental frequencies for +15% and -15% are considered, their results showed that (SAIVD-TMD) is similar to ATMD, however it less power consuming, additionally it robust as it continue to decrease the response ever with structural stiffness changes.

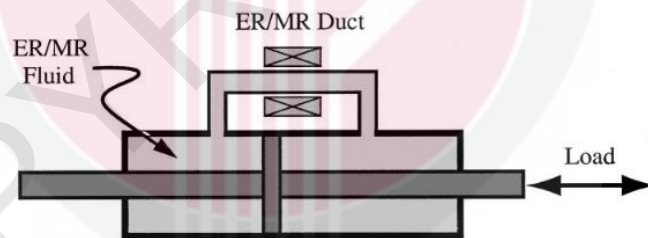
Wang et al. [25] developed a semi-active tuned liquid column damper with magneto-rheological fluid (MR-TLCD). Using MR was to adjust damping performance of conventional TMCD by changing magnet field and hence standing for different structure and load uncertainties.



a) Variable-orifice damper



b) Controllable Fluid Damper



c) Large Scale of MR-Fluid damper

Figure 2.1: Schematic of semi active devices [4]

The equivalent linear method was used to develop stochastic response analysis method and the effectiveness of developed device for suppressing a wind induced response of 50 storey residential building (located in Tokyo, Japan) was investigated, they concluded that there is an optimal relation between tuning frequency ratio and the applied magnet field in order to achieve maximum reduction in response, additionally, the performance of MR-TLCD increases with the increase of mass ratio, this performance is better in terms of acceleration mitigation than displacement.

Using a numerical and experimental analysis model of a 2-DOF structure, Oliveira et al. [26] examined the performance of multiple control strategies to control structural response of a semi-active base isolated structure equipped with magneto-rheological (MR) control device under seismic excitation. The strategies were: integral controller with on-off algorithm (ICOO), linear quadratic regulator with on-off algorithm (LQRCOO and LQR2COO), and model predictive controller (MPCOO), the considered algorithms are of force feedback type. The results were compared with the optimum passive control system and showed that all the semi-active strategies outperformed passive cases.

Ferreira et al. [27] proposed optimum parameters of a semi-active tuned mass damper (SATMD), their objectives was to find a balance between the amplitude of structural displacements and the level of TMD stroke, they use a phase control strategy (displacement-based ground hook strategy) for this purpose. To manipulate the semi-active version of TMD, magneto-rheological damper as a variable damping device with on-off function was implemented between the primary mass and the structure. By finding the optimum tuning parameters for the most common design scenarios and comparing it with the results obtained by the use of passive TMD and other SATMD methods, they concluded that the performance of SATMDs are increases with the existence of detuning problems and the key of such performance is the reduction of damping ratio of SATMD. Moreover, they concluded that the control device stroke should be constraint by control law, otherwise, tuning parameters may lead to no significant structural displacement reduction.

Gutierrez and Adeli [28] presented a methodology to use a combined control system consists of base isolation control device (passive control) and magneto-rheological control device (as semi-active control), they utilize the concept of game theory and dynamic replicator to develop a control algorithm, they evaluated their methodology by carrying out an experimental work on a benchmark bridge located in southern California subjected to historical near-field earthquake. The Authors stated that proposed algorithm require extensive sensitivity analysis to obtain optimum control parameters which it may be time consuming, thus they suggested further studies to utilize multi-objective pareto-based optimization as an alternative to find replicator dynamics parameters.

Wasilewski and Piskarski [29] studied the adaptive efficiency of near-optimal switching control law to build an adaptive semi-active vibration control system, their study was carried out on a numerical model consisting of simple flexible beams furnished with a set of semi-active viscous dampers and subjected to moving load with three high non-uniform cases of acceleration, deceleration and temporary halt phases. The results were compared with related optimal passive and open-loop control systems and showed that the proposed method significantly reduced overall structure deflection and under-moving load deflection, Also, the average difference between the proposed controller and optimal control is 1.8% when measured by performance indices.

Peng and Zhang [30] utilized a PSO-based magneto-rheological vibration control system as a developed scheme for high-efficiency realization for semi-active control of structures deployed with MR dampers and excited by stochastic earthquake ground motion. By equipping two MR (one in the first storey and the other in the third storey) and using the integrated design approach presented by the authors in the optimization of dampers parameters, a six-storey six DOF shear wall structure was numerically tested to validate the presented methodology. The results showed that the reliability-based semi-active vibration control strategy produces a safer and serviceable structure than statistical moment-based control optimization and the integral design procedure for control parameters attained an efficient balance between cost and control effectiveness by reducing inter-storey drift, attaining almost similar storey acceleration control and larger MR force comparing with separated design procedure (straightforward procedure).

Bakhshinezhad and Mohebbi [6] proposed a new methodology for designing a semi-active Fluid viscous damper (SAFVD) control system for nonlinear frames under the effect of earthquake excitation, their methodology is based on developed elitism non-sorted genetic algorithm (NSGA-II) with multi-objective discrete functions. Inter-storey drift and absolute acceleration were chosen as safety and convenience criteria respectively. To implement uncertainty of input excitation, mean response for multiple earthquakes was used, while Newmark-based instantaneous optimal control algorithm was utilized to get the proper damping coefficient of the semi-active devices in each time step. An eight-storey nonlinear shear frame deployed with SAFVD was numerically analysed and the result showed that the proposed method provides the effective design of the SAFVD system and produces a wide range of optimal choices for controller design based on safety and convenience criterion. Furthermore, the performance of the SAFVD system improved by increasing the force capacity of the dampers.

A conclusion can be drawn from the presented studies that most research of semi-active control systems of structures focused on developing well-performed control laws that produce optimal damper properties to produce well-adaptive behavior of the structure in responding to dynamic load. Further, most of these researches studied the structures excited by the seismic loads more than other dynamic load patterns.

2.2.3 Hybrid Controllers

Many approaches have been introduced by researchers to implement a combined control system consist of passive and active or semi-active control devices to achieve the required performance, for instance, hybrid mass dampers, semi-active control of base isolation systems, actuators with passive dampers and semi-active tuned liquid column damper with passive dampers are widely used systems, the reader is referred to [31] which presented a good review for this topic. However, this chapter is not intended to review the related literature, instead, it tries to present a comprehensive review of semi-active controllers as well as optimization and control algorithms as they represent most effective factors in designing adaptive structure.

2.2.4 Fuzzy Logic Controllers

Fuzzy Logic was presented by Lotfi Zadeh 1965 [66], it is inspired by how a human making decision when dealing with knowledge that is vague in nature. In other words, the Fuzzy Logic (FL) system emulates human expertise in solving problems.

Since robust systems are defined as ones whose outputs do not change significantly under the influence of input changes, fuzzy Logic (FL) systems are considered robust because uncertainties comprised in both inputs and outputs are used in formulating the system structure itself [67]; sometimes it is used to overcome chattering phenomena while maintaining system stability [68]. Nevertheless, it has considered as an example of model-free compensators. The main contribution of Fuzzy Logic (FL) Systems (or Fuzzy Inference Systems) is that a systematic approach is clearly defined to convert a fuzzy rule base into nonlinear mapping [69].

2.3 Control Algorithms

Although the performance of adaptive structures depends on many criteria, control algorithms represent the most effective factor in the successful development of the adaptive structure. This importance increases with the increase of structural size and the performance level considerations as the vibration control system's design process becomes more complicated regarding dynamics load variation and varying properties of structural material besides other operation and reliability requirements.

Early researches in structural engineering were using existing computational algorithms to control structural vibrations, those algorithms were based on Linear Quadratic Regulator (LQR) and Linear Quadratic Gaussian (LQG), which are basically developed in other fields such as aerospace, however, recently, researchers shifted to develop their own control algorithms and approaches to manipulate special design requirements of civil engineering structures [31].

Generally, the role of control algorithms consists of getting the structural real-time response, evaluating existing structure state according to knowledge bases, utilizing computational control to change structural characteristics (by means of vibration control devices) and improving the performance of control function using past events [32].

There is more than one classification for adaptive control algorithms. Traditionally, it is classified into two categories: model-based algorithms (LQR and LQG are common examples) and non-model-based algorithms (such as fuzzy logic and genetic algorithms). The former requires control parameters to be defined, and it is useful for the observation of control parameters variation, conversely, the latter approach doesn't give a physical interpretation of the system behaviour, but, it is efficient in addressing

nonlinearity and uncertainty of the system [5]. The next subsection is presenting a review of the recently developed structural vibration control methodologies during the past two decades.

2.3.1 Recent Developed Control Algorithms

Wavelet-hybrid feedback-least mean square (LMS) algorithm was proposed by Adeli and Kim [33] as a robust control algorithm for civil structures. Based on the fact that the response of most civil structures is not significantly affected by high frequencies of external excitation, the writers utilized a low-pass filter with the filtered-x LMS controller algorithm to overcome the drawbacks of using each filter alone. The low-pass filter is based on wavelet transform filter and it is used to filter out higher frequencies' elements over defined cut-off frequency. The developed control algorithm was applied on a reference active tuned mass damper (ATMD) system subjected to hypothetical ground acceleration signals, and simulated numerically, further, a benchmark scaled two-dimensional model of a structure with three storeys and subjected to two types of one-dimensional ground motion were also tested. The authors concluded that the proposed algorithm is effectively controlling both steady and transient vibration without any additional computational cost; furthermore, it is useful to enhance the performance of existing feedback control algorithms.

Bel Hadj Ali and Smith [34] presented the vibration control of a five-module active tensegrity structure as a multi-objective optimization problem. The control commands are identified using stochastic search through Probabilistic Global Search Lausanne (PGSL) and PROMETHEE outranking strategy. The rule of the proposed active control system is to attenuate vibrations by shifting values of natural frequencies away from excitation by commanded contracting or elongating the active struts.

To overcome the limitation of using neuroemulator and neurocontroller algorithms especially in high rise building structures under nonlinear conditions, Jiang and Adeli [35] presented a new neuro genetic control algorithm as an intelligent control algorithm to optimize the control force of nonlinear active controller, the authors used dynamic fuzzy wavelet neuroemulator proposed by them in a past work [36] to predict the future nonlinear structural response while floating point genetic algorithm were used to find optimal control force by searching in each control loop during earthquake excitation (see Figure 2.2). The proposed strategy was validated by examining numerical structural 3D models of 12-storey and 8-storey irregular steel structures subjected to three different earthquake excitations. The writers concluded that the new strategy is significantly mitigating response of large building structures with vertical and horizontal irregularities.

Kim and Kang [37] proposed a control methodology by combining between both groundhook control algorithm and skyhook control algorithm, the hybrid control algorithm was applied on adjacent buildings subjected to earthquake and connected by magneto-rheological (MR) semi-active damper. The results showed that the proposed methodology is performed well in controlling the response of the two adjacent buildings and can be applied to control adjacent parallel buildings under extreme wind and other dynamic load, however, further studies should be conducted to find the best location of MR dampers.

Although there are several techniques available for predicting and quantifying uncertainties in environmental loads, their accuracy is not always assured due to potential influences from factors like data availability, data quality, and sample size [38].

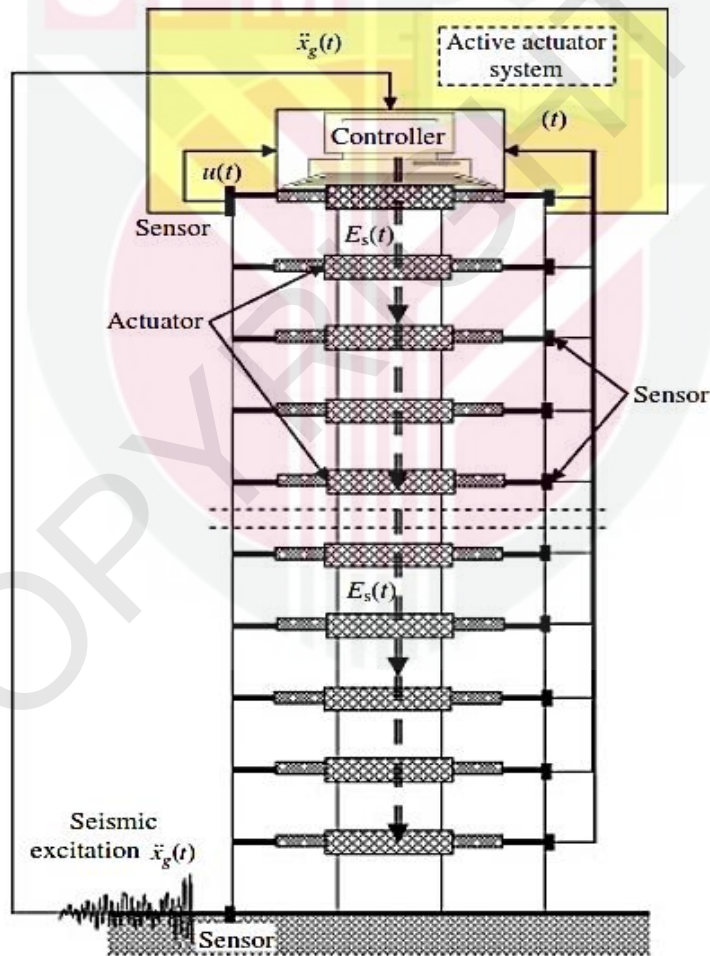


Figure 2.2: Schematic of an active control system in one direction [36]

Fuzzy logic controllers (FLCs) are considered as one intelligent controls capable of withstanding uncertainties and nonlinear behavior in both environmental loads and structural properties [39]. Many researchers had been developed fuzzy logic-based control algorithms by unification with other methods, particularly neural networks and genetic algorithms. However, the performance of such control algorithms mainly depends on training data and network training effectiveness [40]. A combination of a fuzzy logic control algorithm (FLC) and genetic algorithm (GA) was utilized by Pourzeynali S. et al. [41] to mitigate the structural response of high-rise buildings under the effect of earthquake excitation. The proposed algorithm was applied to a numerical model of a shear walls 11-storey structure equipped with an active tuned mass damper at the top storey and subjected to four different seismic motions. The control system used top story displacement as an objective function while both displacement and velocity were used as feedback gain. The results showed that the proposed system produces the best response reduction and larger control force in comparison with the equivalent system controlled by LQR algorithm, in addition, the authors concluded that GA optimizer is a very suitable tool to optimize FLC of many parameters. Kaveh and Khademhosseini [42] employed a fuzzy logic inference system and charged system search (CSS) algorithm to command the optimal voltage for MR damper as a supplementary energy dissipation device in a ten-story shear building with a tuned mass damper (TMD) at top story. The proposed strategy showed a good capability to mitigate structure response and overcome the complexity of modelling a TMD system. Xu et al., [43] employed an adaptive Fuzzy Logic function to develop a Fuzzy Variable Fractional-Order Sliding Mode Control (FVFOSMC) for the purpose of vibration control in uncertain building structures. The findings demonstrated that the effective approximation of the sliding surface facilitated by Fuzzy Logic successfully addressed the issue of chattering in the control system's response.

Zhou et al. [44] introduced the concept of "online" structural vibration control as they presented an adaptive fuzzy logic vibration control strategy. This strategy involved real-time prediction of the structural states and control device commanding voltage utilizing Fuzzy Logic Controllers. To accomplish this, Lyapunov function was employed to minimize the error between the desired and measured outputs. The results of their study demonstrated the effectiveness of the proposed strategy in mitigating the response of earthquake-induced structures with uncertainties. Wang and Adeli [45] integrated a self-constructing wavelet neural network (SCWNN) with an adaptive fuzzy sliding mode control approach. The algorithm was intended to pursue adaptive control of structure under extreme dynamic events in which the physical properties of structure (such as stiffness and damping ratio) are not entirely known as they may change during these events. Furthermore, in this model identification and control are computed simultaneously which make the control more applicable for real life applications. A benchmark seismically excited highway bridge was modelled with the proposed algorithm and the results showed that although SCWNN model does not rely on known properties of structure, it produces same performance as LQR model.

Wang and Adeli [46] presented a new filtered sliding mode control (SMC) algorithm based on the equivalent control force principle instead of computing control force by Lyapunov-function based control design and by exploiting low-pass filter to reduce the structural response for an active vibration control system of a high rise building excited

by wind load. A benchmark 76-storey concrete building equipped with active tuned mass damper ATMD was used for the validation. The results showed that the new approach has better performance in comparison with LQR and other SMC approaches, especially in terms of reducing control force and control energy.

To overcome the shortcomings of well-known H_2/H_∞ robust control algorithms in terms of structural response uncertainties, a new discrete-time robust H_2/H_∞ control algorithm was presented by Li and Adeli [47]. Based on the bounded real lemma and the linear matrix inequalities (LMI) theories, the robustness of the proposed method was proved. The uncertainties parameters of the studied structure were implemented in the time domain as opposed to frequency for practical purposes, two numerical structures were used to validate the effectiveness of the developed algorithm; a three degree of freedom 3-storey shear frame structure with the active bracing system in each storey and a 10-storey ten degree of freedom structure with ATMD equipped on the top floor. The authors stated that the new control algorithm is promising for practical active, semi-active and hybrid control systems for the large and real-life structures and it is suitable for integration with health monitoring of structures.

Due to the vulnerability of centralized control systems to single points of failure [48], researchers have increasingly turned to decentralized control systems. In decentralized control systems, the structure is divided into substructures, each with one or more controllers. These controllers rely on local measurements to make control decisions instead of relying on global measurements as in centralized systems. By defining the intelligent agent as an autonomous entity which observes by the mean of sensors and acts simultaneously upon an environment in an adaptive way, Soto and Adeli [49] developed two new methodologies in order to overcome the drawbacks of the centralized control system. The proposed methods were a single-agent centralized replicator controller (CRC) and a decentralized multi-agent replicator controller (MARC) (see Figure 2.3). The new strategies were applied to a benchmark 20-storey moment resistance steel frame building subjected to near and far field historical accelerograms of four different natural and artificial earthquakes. The control outcomes are compared with the traditional centralized and decentralized LQR controllers. The results showed that the use of decentralized agents improved the reliability of the control system, however, the authors declared that further studies should carry out to examine the stability of the proposed algorithm using passivity theory.

To optimize the key parameters of CRC and MARC, the authors extended their research and integrated the aforementioned methods with a multi-objective optimization algorithm based on the neural dynamic model NDAP (patented by Adeli and Park (U.S. patent 5,815,394 issued date on September 29, 1998)) [50] presenting many-objective control optimization to find the optimal values of MARC growth rates with the persuasion of minimum energy consumption and maximum structural performance (by minimizing acceleration and inter-storey drift). The proposed algorithm was applied again on the previous benchmark structure under the same load conditions and the results showed that MACR distributes the resources in a more efficient manner than CRC and other control approaches.

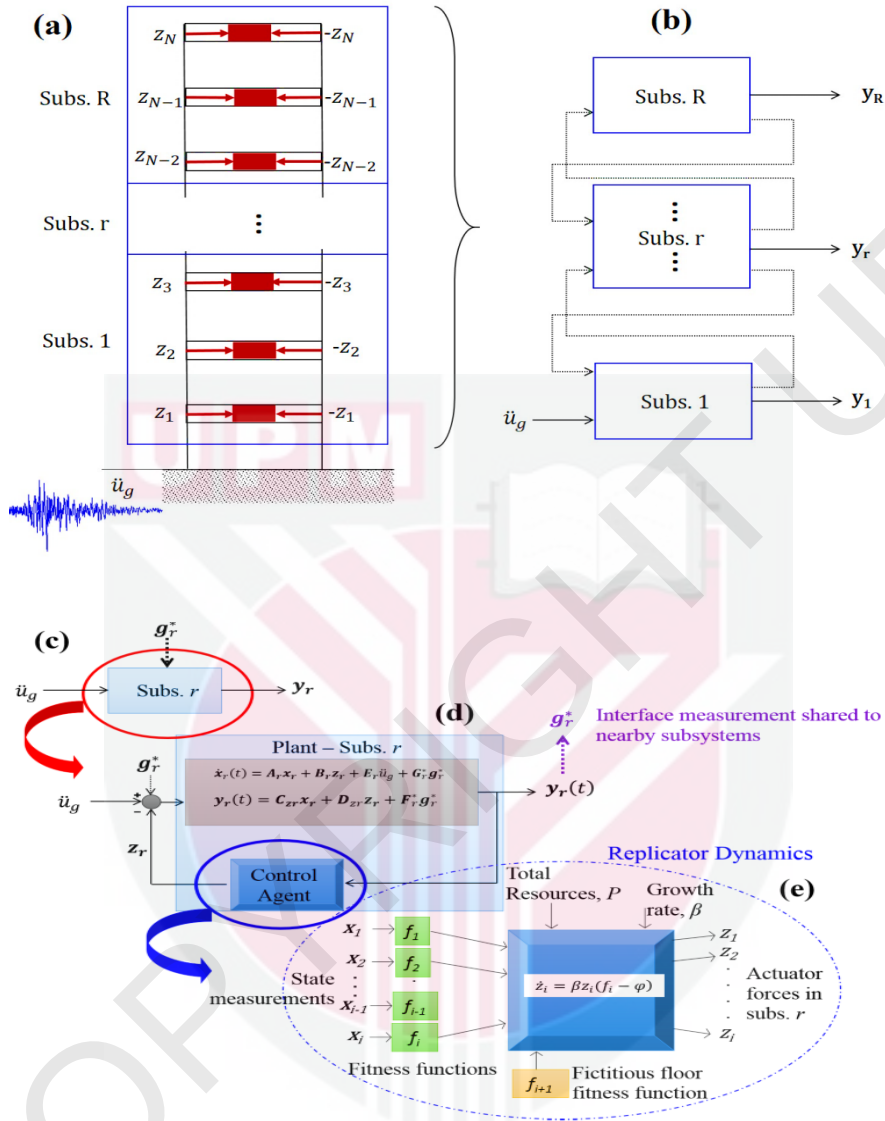


Figure 2.3: Integration of replicator dynamics, agent modeling and decentralized control system [41]

The nonlinear response of plan irregular controlled structures with multi-tuned mass dampers (MTMDs) was studied by Khazaei et.al.[51]. GA algorithm and SAP2000 analysis software were utilized to get the optimal position for TMDs, the results showed that distributed mass dampers were more effective than one-point mass in mitigation the structural response under nonlinear time history earthquakes.

With the development of high-strength materials, which are more flexible and lighter in weight, and due to the increasing demand on high rise buildings, recent design trends have been shifted to consider more criteria in addition to strength and serviceability factors; such criteria comprise performance, occupant perception and comfort, reliability and sustainability [23]. Zafarani and Halabian [52] proposed a new method to implement the nonlinear structural properties in a semi-active control system for structures with a combined translation-torsional response due to structural irregularities. The new methodology is based on the modified clipped optimal model as a model-based control system deployed with MR dampers, the change in structural stiffness during earthquake events is traced by utilizing the pushover analysis method to get the nonlinear response of the uncontrolled structure and save it as off-line data, then these data had been used as a supervisory tool to evaluate the structure response at each time step and updating stiffness related values involved in the control model. Zhang et al.[53] proposed a semi-active multiple tuned mass damping system for wind-induced structures. They employed a displacement reducing bang-bang control algorithm and utilized the mass of the outer double-skin facade (DFS) in their approach. However, their methodology did not account for the effects of multidimensional and multidirectional wind loads. Steffen et al. [54] introduced two concepts for adaptive structures in high-rise buildings experiencing static wind loads: stress-free adaptations and element moment actuation. These concepts involve manipulating the structure's adaptivity by applying a unit actuation load, followed by studying the resulting passive load-bearing behavior. However, their approach had not evaluated under the effect of dynamic load. Xu et al. [55] presented closed-form design formulas for Tuned Mass Damper Inerter (TMDI) in Vortex-Induced Vibration (VIV) control of bridges. These formulas consider nonlinear aeroelastic effects and sensitivity to structural damping. They provide the necessary TMDI frequency and damping ratio based on TMDI mass, inertance, and inerter arrangement to achieve the desired equivalent damping. The proposed formulas are validated using wind tunnel experimental data and found to offer a higher accuracy and improved control efficiency compared to existing design formulas that assume an undamped single-degree-of-freedom primary structure.

It can be concluded that although the concept of control algorithm is generally analogous, there are a wide range of parameters affect the performance of the control algorithm which it the key of the implementation of adaptive technology in structures, this opens the doors for researchers to continuously develop new approaches and methodologies.

Li and Adeli [39] presented a good review of most used control algorithms in structural engineering, their review included pros and cons for each approach (see Table 2.1). In addition, they proposed many research trends for future studies, the reader can refer to recently stated reference for extra information.

2.4 Optimization Algorithms

One of the significant developments in computer-aided discipline was the use of computers for both simulating and design of engineering problems. Such advancement led to the emergence of automatic design approach in which computers are utilized to solve problems and search for the best solution with less human involvement.

Table 2.1: Advantages and disadvantages of active control algorithms [43]

Method	Advantages	Disadvantages
1 Linear control algorithms		
(1) LQR control	Simplicity of design Ease of implementation	Accurate linear structural model Requirement of full-state feedback Mainly used to control linear structures
(2) LQG control	Simplicity of design Ease of implementation No requirement of full-state feedback	Accurate linear structural model Assuming that disturbance is the Gaussian white noise processes Mainly used to control linear structures
(3) Pole arrangement control	Simplicity of design Ease of implementation	Accurate linear structural model Mainly Used to control linear structures Requirement of full-state feedback
(4) PID control	Simplicity of design Ease of implementation	Accurate linear structural model Mainly used to control linear structures Requirement of full-state feedback
2 Robust and nonlinear control algorithms		
(1) H_∞ control	No requirement of accurate structural model Ease of implementation Improved robustness	Complexity of design Mainly used to control linear structures
(2) Optimal polynomial control	Used to control linear/nonlinear structures	Complexity of design Accurate linear/nonlinear structural model Existing difficulty to minimize the performance index
(3) SMC control	No requirement of accurate structural model Ease of implementation Used to control linear/nonlinear structures Improved robustness	Excessive chattering effect
(4) Intelligent control	No requirement of accurate structural model Improved robustness and reliability Improved control performance Used to control linear/nonlinear structures	Complexity of design
3 Probabilistic control algorithms	No requirement of accurate structural model Used to control linear/nonlinear structures Better robustness and reliability	Complexity of design
4 Decentralized control algorithms	Better robustness and reliability Higher computational efficiency Lower energy requirements	Complexity of design

The designer needs only to formulate, prepare and set up the problem for the computer [56]. To enable the computer for carrying out this task, an optimization algorithm should be defined to command the computer to find the optimum solution among many available solutions.

The classical approach for optimization of engineering problems was a gradient-decent-based algorithm, in this approach; the optimum solution is determined by finding the derivation of the problem solution; however, the main drawback of this method is the high probability of trapping in the local solution (local optima).

Stochastic optimization techniques are the alternative technique to overcome the shortcomings of the previous approach [44]. According to the theory of No Free Lunch (NFL) for optimization, the area is open for researchers to develop existing algorithms or propose new ones [57]. However, stochastic optimization can be classified into two categories; single solution-based algorithms and population-based algorithms, simulate annealing (SA), local searches, and hill-climbing are examples of the former category, meanwhile, particle swarm optimization (PSO), genetic algorithm (GA), ant colony optimization (ACO), artificial Bee colonies (ABC) and global search algorithm (GSA) are the most used algorithms amongst the second category algorithms [45].

Hejazi et al. [58] utilized the genetic algorithm as a control algorithm for the active control system. By the use of neural network as an analysis tool and then integrating it with GA, the optimum stiffness of an active variable stiffness damper is gotten at each time step (see Figure 2.4). The method was validated using a numerical model of a 3-storey concrete frame subjected to actual earthquake records. The results showed excellent performance of the proposed algorithm in comparison with the uncontrollable version of the studied structure.

Askari [59] used non dominated sorting genetic algorithm (NSGA-II) as an optimization tool to find the best position and number of the actuators in high-rise buildings subjected to different earthquake excitations. The results showed the effectiveness of the proposed algorithm in finding the best number and optimum distribution of actuators for each case of external load magnitude and structure properties.

Hejazi et al. [60] utilized multi-objective genetic algorithm GA to optimize the properties of the fluid viscous damper of a passive control system, the algorithm deployed by using the damping coefficient of the dampers as a design parameter (each damper considered as a gene and the dissipation system simulated as a chromosome,

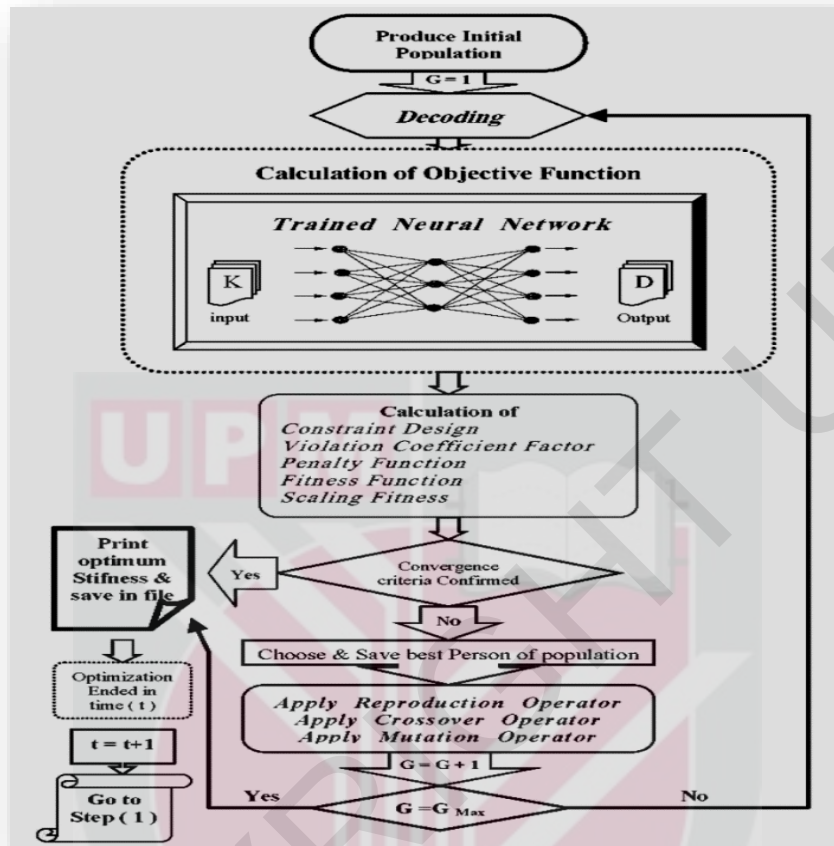


Figure 2.4: Proposed algorithm for active control system using GA [46]

Figure 2.5, and the storey drifts in three dimensions as the objective functions. Further, the permissible storey drift and the number of plastic hinges are considered as the design constraints in the penalty function. The methodology was applied to a three-dimensional 5-storey numerical model of a concrete building under El Centro earthquake and the results showed the effectiveness of the proposed algorithm in reducing structural response and increasing its safety level.

Jabbar et al. [61] exploited particle swarm optimisation algorithm PSO to search the optimum correlation factor of damage frequencies for ultra-high performance fibre reinforced concrete tower (UHPFRC). The proposed algorithm was intended to find a correlation factor to predict damage frequencies by knowing the natural frequencies of the structure under healthy conditions. FEM for different heights of UHPFRC was developed and an experimental test for the evaluation purpose of the numerical models was carried out. The predicted correlation factor was validated by an extra FEM case study of a 15 m height tower. The authors reported that the proposed method successfully predicted the correlation factor with high accuracy and consistency.

Although there are numerous studies pivoted about the optimization algorithms, each algorithm has its advantages and disadvantages. The most applicable algorithms to use in structural engineering problems are those based on stochastic-population techniques as they are more sufficient in the exploration and exploiting of the solution space.

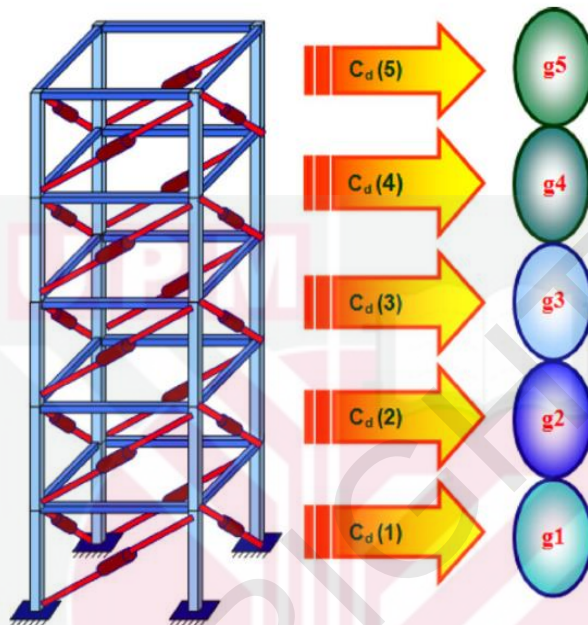


Figure 2.5: Simulating of viscous dampers as genes [48]

It is revealed from a critical review of the literature that control algorithms play the leading role in the performance of structural vibration control systems. The real-time controllers, which continuously evaluate the structure's response and command the control devices according to the unpredictable applied dynamic loads to the structures, are the most robust way to ensure the system's reliability to withstand uncertainties in external excitation and structural response.

The model-based algorithms have a limited capability in carrying the uncertainties in external excitations and structural properties since their parameters depend on the available data utilized at deriving phase.

Although intelligent controllers such as fuzzy logic-based controllers are more robust than model-based controllers, their performance depends on offline training data, i.e., despite the real-time response of the control system, the controller's parameters are not changed in real-time. Table 2.2 presents the findings and limitations of the most inspiring control strategies.

2.5 Chapter Summary

The existing body of research on controlling building responses with active controllers has proposed various strategies. However, the effective mitigation of vibrations in tall buildings using active controllers is often associated with high energy consumption. This cost factor has led to a focus on semi-active control devices as an alternative. Most studies in this area concentrate on developing well-performing control laws to optimize damper properties, ensuring adaptive behavior in response to dynamic loads, particularly seismic loads. This understanding emphasizes the key role of implementing adaptive technology in structures and encourages continuous development of new approaches and methodologies.

While numerous studies explore optimization algorithms, each algorithm has its set of advantages and disadvantages. Stochastic-population techniques, particularly in structural engineering problems, are considered more efficient in exploring and exploiting the solution space. Although intelligent controllers like fuzzy logic-based controllers demonstrate robustness, their performance relies on offline training data, introducing a consideration of parameter adjustments in real-time responses.

Table 2.2: A summary of the most interesting vibration control strategies

Author	Control Strategy	Application	Findings, Limitations and Drawbacks
<i>X. Jiang and H. Adeli [35]</i>	Neuro-genetic control algorithm	High-rise building structures under nonlinear conditions	Mitigates response in large building structures with irregularities. However, Its efficiency depends on the future response prediction method.
<i>G. C. Kim and J. W. Kang [37]</i>	Ground hook and skyhook control algorithm	Adjacent buildings connected by MR semi-active damper 11-storey shear wall structure with ATMD under earthquake excitation	Hybrid control algorithm performed well in earthquake conditions/Further studies needed for optimal MR damper location.
<i>Pourzeynali S. et al.[41]</i>	Fuzzy logic control algorithm (FLC) and genetic algorithm		Mitigates structural response/Performance depends on training data and network training effectiveness.
<i>Zhou et al. [44]</i>	Adaptive fuzzy logic vibration control strategy	Real-time prediction of structural states	Effective in mitigating response of earthquake-induced structures with uncertainties. Model-based control system.
<i>N. Wang and H. Adeli [45]</i>	Self-constructing wavelet neural network and adaptive fuzzy sliding mode control	Seismically excited highway bridge	Performance comparable to LQR model without relying on known properties of the structure.
<i>Z. Li and H. Adeli [47]</i>	Discrete-time robust H_2/H_∞ control algorithm	Structures with uncertainties	Robustness proved based on bounded real lemma and LMI theories. Suitable for integration with health monitoring.
<i>G. Soto and H. Adeli [49]</i>	Single-agent CRC and decentralized multi-agent MARC	20-storey moment resistance steel frame building	Further studies needed to examine stability using passivity theory.
<i>G. Soto and H. Adeli [50]</i>	Multi-objective optimization algorithm NDAP	Optimization of CRC and MARC growth rates	The proposed algorithm requires extensive sensitivity analysis to obtain optimum control parameters which it may be time consuming.

Table 2.2: Continued

<i>Zafarani and Halabian [52]</i>	Modified clipped optimal model as a model-based control system	Semi-active control system for structures with combined response Wind-induced structures with semi-active multiple tuned mass damping system Adaptive structures in high-rise buildings experiencing static wind loads	Its performance depends on available offline data from pushover analysis which utilized as a supervisory control.
<i>Zhang et al.[53]</i>	Displacement reducing bang-bang control algorithm		Did not account for multidimensional and multidirectional wind loads.
<i>Steffen et al.[54]</i>	Stress-free adaptations and element moment actuation		Concepts involve manipulating structure's adaptivity under static wind loads, not evaluated under dynamic load.

A critical review of the literature underscores the pivotal role of control algorithms in the performance of structural vibration control systems. Real-time controllers, continuously evaluating a structure's response and adapting to unpredictable dynamic loads, are identified as robust solutions to ensure system reliability in the face of uncertainties. Hence, the overall objective of this research is to synergize the benefits of fuzzy logic inference systems and stochastic optimization algorithms, aiming to develop a novel adaptive vibration control system capable of addressing the limitations inherent in existing systems by real-time controller optimization, responding to external excitation, and training itself in real-time for full adaptivity feature



CHAPTER 3

METHODOLOGY

3.1 Introduction

The main goal of this study is to present an adaptive, applicable, and robust vibration control system capable to control the structural response under the effect of dynamic load through integrating the advantages of Fuzzy logic inference system, MR dampers and stochastic optimization. Accordingly, the parameters for the developed vibration control system is the control law itself while the criteria is the effectiveness of the developed system to mitigate the structural response within the design and serviceability limits. To this end, two novels vibration control systems for the building structures furnished with MR dampers have been developed and evaluated.

This chapter is laid into two parts; in section 3.2, a step-by-step development of a new Fuzzy Logic-based Multi-Verse Optimum real-time vibration Control system (FLMVOC) for structures under wind and seismic excitations is presented. A novel online fuzzy logic multi-verse optimal control (Online-FLMVOC) system has been developed in section 3.3. The shortcomings of the basic FLMVOC strategy have been overcome by allowing the system to update its controller's parameters in real-time. Then the best controller is smartly selected amongst the best solutions produced from the optimization process so far.

The proposed systems are assessed by applying them to a three-story shear building subjected to different seismic load records; after that, the robustness of the developed vibration control system is tested by implementing it in a full degree of freedom wind-sensitive high-rise buildings subjected to multidimensional wind load.

A benchmark 3-story steel structure under the effect of reference earthquake time history loads has been simulated using state space representation. The rules and membership functions of the Fuzzy Logic Inference system have been developed. The rules weight and membership functions parameters have been selected as design variables in the Optimization algorithm, then the optimization is launched on the complete structural vibration control system to derive the best FL controller. To this end, the evaluation for the proposed methodology has been done on the same structure under the effect of multiple earthquakes and then the results were compared with the well-known control strategies from literature.

Then the robustness of the developed FLMVOC was assessed by applying it to a high-rise wind-sensitive building under the effect of multi-attack angle wind load.

In section 3.3, the development of Online-FLMVOC is presented. The novel algorithm hybridizes fuzzy logic inference system and multi-verse optimization algorithm; moreover, it utilizes three ideas; parallel processing, decentralized system, and optimal controllers' memory as a developing tool.

To assess its efficiency in diminishing structural dynamic response, the developed Online-FLMVOC system has been implemented in a three-story shear building subjected to seismic load and 76 story benchmark building subjected to multi-attack angle wind load.

Figure 3.1 shows a flow chart for the progress of this chapter. The rest sub-sections of this chapter elaborate on the methodology in detail.

3.2 Development of Fuzzy Logic Multi Verse Optimal Control System (FLMVOC)

In this research an attempt has been made to develop a vibration control system based on the fuzzy logic (FL) inference system, and it utilizes the power of multi verse optimization (MVO) as a powerful stochastic optimization method. The development process for the proposed Fuzzy Logic Multi Verse Optimal Control (FLMVOC) System is summarized through the following steps:

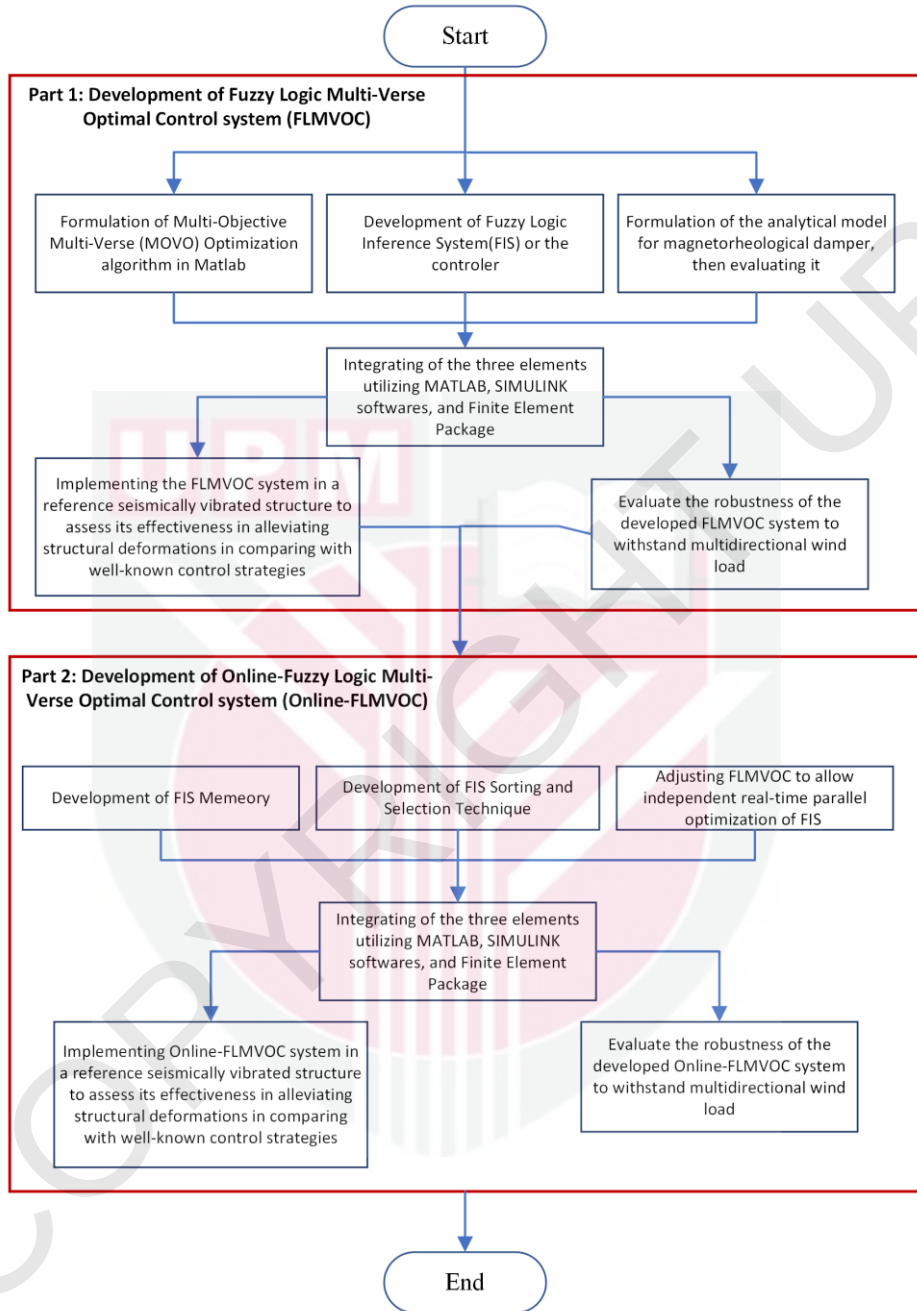


Figure 3.1: A flow chart for the progress of chapter 3

1- The initial step was development of a fuzzy logic controller. In this step, the controller's inputs, outputs, position of each membership function, in addition to fuzzy base rule weight are formulated and considered as the optimization's design variables.

2- The analytical model for Magnetorheological (MR) damper is formulated.

3- The proper platform to model the considered structure is developed.

4- Development of an integrated and synchronized system to connect Matlab software and its Simulink to run optimization process and also real-time controller mechanism to the finite element program such as ETABS program to simulate and analyze the structure under applied load and return the structural response to MATLAB for continue optimization and also control process.

5- All optimization parameters are defined include of optimization's variables, optimization's constraints, penalty function, objective function, number of iteration (max time), number of universes (population), maximum archive size, number of objective functions and number of independent iterations.

6- Define and initiate the optimization process through following steps:

6.1- For each Iteration:

6.1.1- Initialize the universes (each universe represents a fuzzy logic controller)

6.1.1.1- For each universe:

- i) Simulate the structure and apply the time history load
- ii) Conduct analysis and evaluate the structural response
- iii) Calculate the objective function
- iv) Check the constraints and assign penalty function

6.1.1.2- Save the structural controllers (Universes) in the archive

6.1.1.3- Rank the solutions (fuzzy logic controllers) according to objective function

6.1.1.4- Sort and update the archive

6.1.1.5- Choose the best structural controller (solution), the high ranked solution.

6.2- Start the next iteration

6.3- When the iterations are completed (see Figure 3.2 and section 3.2.3), select non dominated structural controllers (solutions) from the archive and put it in pareto front archive, these are called the pareto optimal solutions.

6.4- Run the next independent iteration and repeat the previous steps (6.1-6.3).

6.5- Update the pareto front archive and plot for the pareto optimal solutions.

7- The optimal fuzzy logic controller is selected from pareto optimal solutions, then it is implemented in the vibration control system to command the MR damper.

Figure 3.2 shows a flowchart for the proposed optimal control strategy. The above-mentioned steps are demonstrated in details in the following subsections.

3.2.1 Developing of Fuzzy Logic Controller (FLC)

The design of FL systems is based on several assumptions, which are followed in this research and stated below [67]:

- The plant (i.e., controlled structure in our study) is observable and controllable.
- There exists a body of knowledge comprising a set of linguistic rules or a set of data (input-output) from which rules can be extracted.
- There is at least one solution exists.
- The controller will be designed within an acceptance range of precision.
- The problems of stability and optimality are not addressed explicitly.

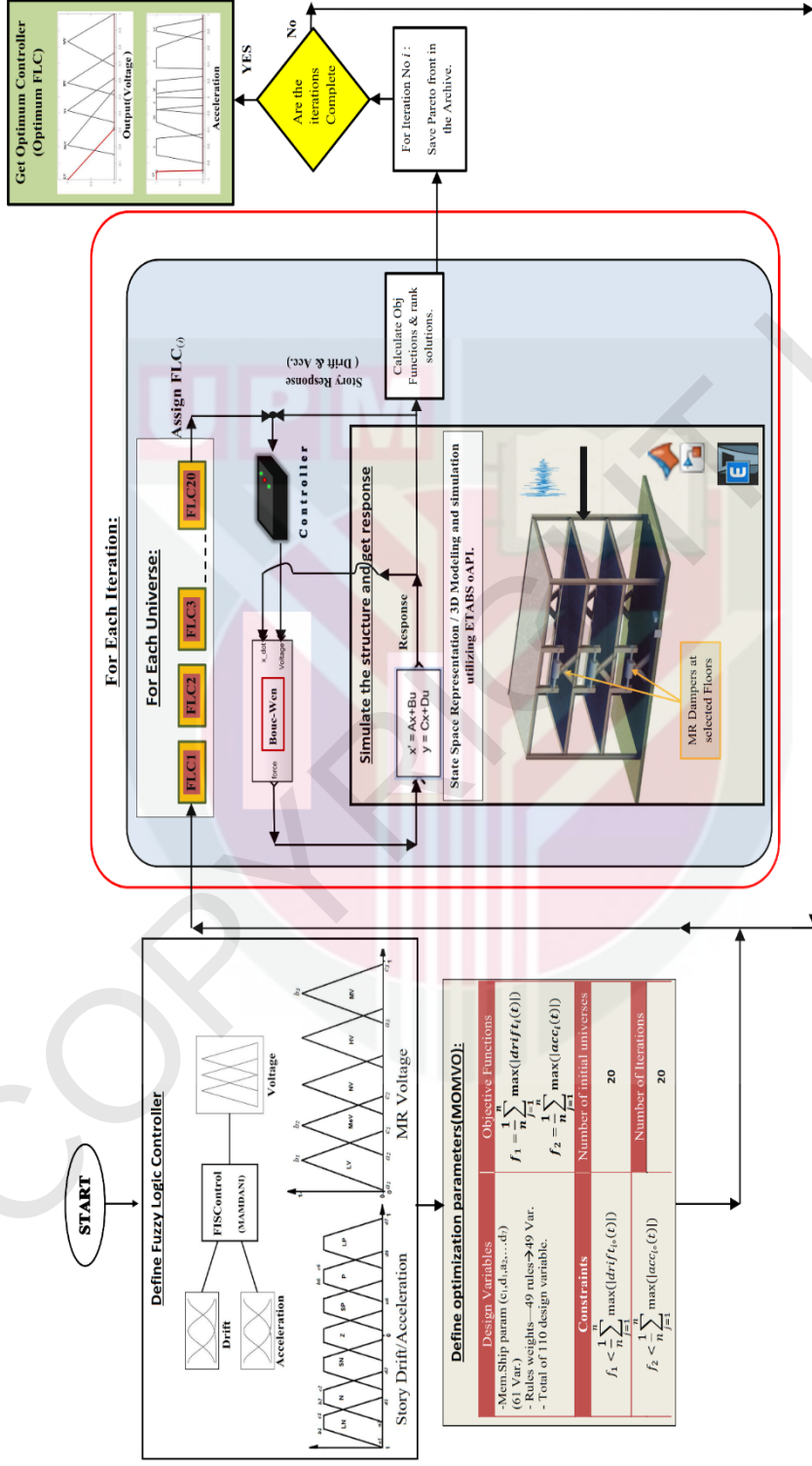


Figure 3.2: A flowchart for the developed FLMVOC control system

Figure 3.3 shows a graphical presentation for the process of developing any Fuzzy Logic (FL) system which can be elaborated as follows:

1. Identify the variables (inputs, states and outputs) of the plant.
2. Divide the universe of discourse or the interval spanned by each variable into a number of fuzzy subsets, assigning each a linguistic label (subsets include all the elements in the universe).
3. Assign or determine a membership function for each fuzzy subset.
4. Assign the fuzzy relationships between the inputs or states; fuzzy subsets on the one hand and the outputs fuzzy subsets on the other hand, thus forming the rule-base.
5. Choose appropriate scaling factors for the input and output variables in order to normalize the variables to the $[0,1]$ or the $[-1,1]$ interval.
6. Fuzzify the inputs to the controller.
7. Use fuzzy approximate reasoning to infer the output contributed from each rule.
8. Aggregate the fuzzy outputs recommended by each rule.
9. Apply defuzzification to form a crisp output.

3.2.1.1 FLC Parameters and Base Rules

In this study, a feedback fuzzy logic controller was developed by defining two inputs: story drift and story absolute acceleration. System output is proposed to be the commanding voltage for the MR damper. Membership functions for the inputs were assumed as trapezoidal functions while the output was formulated using triangular membership functions. Each input has seven shape functions, however, only five membership functions was utilized to define the system output.

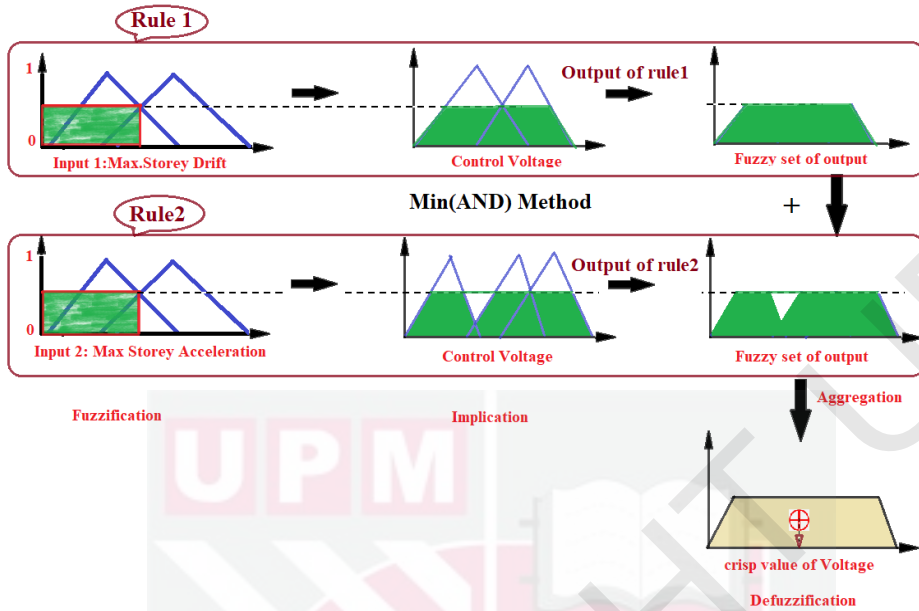


Figure 3.3: Graphical representation of fuzzy logic inference system process

Four parameters (a_i, b_i, c_i, d_i) per each input membership function have to be defined, representing the position for each trapezoidal membership function, while only three position parameters should be defined for each output membership function. The graphical form of the proposed membership functions and the linguistic representation for the proposed base rules are shown in Figure 3.4.

It is known that the design of fuzzy logic controllers depends on the designer's experience since there are no fixed procedures for it [63]. Therefore, the base rules were proposed according to the expected performance of the MR damper for different load patterns and the desired reduction in a specific response. Accordingly, different base rules were proposed to control the structures under the effect of the earthquake and wind excitations. When an earthquake happens, the desired control action is to reduce story displacement or drift response. In contrast, controlling the structural acceleration response is more vital when the structure is subjected to the wind load.

The rules define the linguistic relationship between inputs and outputs, while the rule weights reflect the reliability and allocated contribution of individual rules in the final decision. Table 3.1 and Table 3.2 show the proposed fuzzy logic controller's rules; each considered input (story drift and story acceleration) are mapped into seven zones (membership functions), tracing different structural response values. Forty-nine rules are formulated to manage the controller output for different inputs' cases. For instance, if the story drift is positive (P) value (within excitation direction) and the story absolute acceleration is positive (P), then a high voltage (HV) is desired to avoid the probability of resonant vibration. On the other hand, if the story drift is negative (N) and the

acceleration is positive (P), then only a control force within one-third of the dampers' force capacity (Medium Voltage (MeV)) is desired since higher vibration modes are expected.

Mamdani-type fuzzy inference system has been adopted, here, (MAX) operator is used in fuzzification step, while the truncate (AND) method has been employed in implication step. The crisp values of inputs are generalized in a closed interval $[-1,1]$ by dividing measured response by a predefined design values (i.e., design drift and acceleration), however, voltage crisp value is defined as generalized value relative to maximum current driver capacity of MR damper, hence it interpreted as $[0,1]$ interval.

Again, the method of MAX (AND) was used for aggregation. Moreover, for defuzzification, the centre of gravity method was applied. The FL controller was defined and implemented in the proposed control strategy using MATLAB and the FUZZY LOGIC DESIGNER toolbox [70].

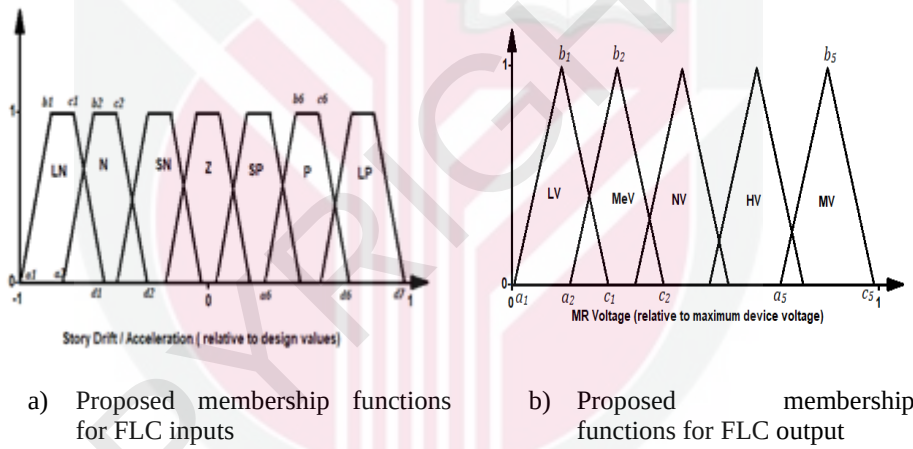


Figure 3.4: FLC proposed membership functions

Table 3.1: Proposed base rules for the FLC (earthquake excited structure)

<i>Drift</i>	<i>Acceleration</i>						
	LN	N	SN	Z	SP	P	LP
LN	MV	MV	HV	MV	MeV	MeV	LV
N	MV	HV	NV	NV	MeV	MeV	LV
SN	NV	NV	NV	MeV	LV	LV	LV
Z	MeV	MeV	LV	LV	LV	LV	LV
SP	NV	MeV	LV	LV	MeV	NV	NV
P	MeV	NV	NV	NV	HV	HV	MV
LP	NV	NV	HV	HV	HV	MV	MV

Keynote: LN: Large Negative, N: Negative, SN: Small Negative, Z: Zero, SP: Small Positive, P: Positive, LP: Large Positive.
 LV: Low Voltage, MeV: Medium Voltage, NV: Neutral Voltage, HV: High Voltage, MV: Maximum Voltage.

Table 3.2: Proposed base rules for the FLC (wind excited structure)

<i>Drift</i>	<i>Acceleration</i>						
	<i>LN</i>	<i>N</i>	<i>SN</i>	<i>Z</i>	<i>SP</i>	<i>P</i>	<i>LP</i>
<i>LN</i>	MV	MV	NV	NV	NV	MV	MV
<i>N</i>	NV	NV	MeV	MeV	MeV	NV	NV
<i>SN</i>	MeV	MeV	LV	LV	LV	MeV	MeV
<i>Z</i>	MeV	LV	LV	LV	LV	LV	MeV
<i>SP</i>	MeV	MeV	LV	LV	LV	MeV	MeV
<i>P</i>	NV	NV	MeV	MeV	MeV	NV	NV
<i>LP</i>	MV	MV	NV	NV	NV	MV	MV

Keynote: LN: Large Negative, N: Negative, SN: Small Negative, Z: Zero, SP: Small Positive, P: Positive, LP: Large Positive. LV: Low Voltage, MeV: Medium Voltage, NV: Neutral Voltage, HV: High Voltage, MV: Maximum Voltage

3.2.2 Magnetorheological Damper (MR):

It is proved that semi-active control devices are considered a superior vibration control system compared to other controllers owing to their efficiency and low power demand. However, the MR damper as a semi-active device is viewed as a prospective device due to its excellent damping performance [30].

In this study, and for evaluation purposes, a prototype of MR damper from Lord Corporation for testing and evaluation was used [71]. The characteristics of this device are shown in Table 3.3. Figure 3.5 shows a schematic view of the MR damper.

Table 3.3: MR damper properties

<i>Typical properties</i>		<i>Electrical Properties</i>	
Stroke Length	∓ 2.5 cm	Peak Power	≤ 10 watt
Extended Length	21 cm	Peak Voltage	≤ 3 volt
Body Diameter	3.8 cm	Current Driver Type	Linear (Current is proportional to applied voltage)
Fluid Volume	50 ml		
Response Time	10 milliseconds		

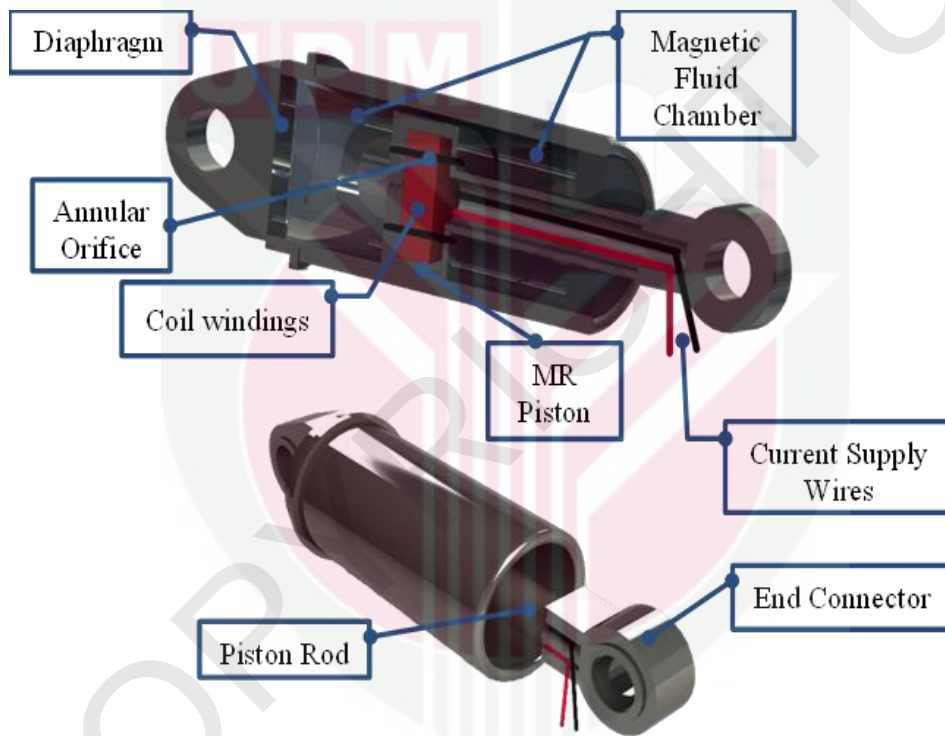


Figure 3.5: A schematic view of MR damper

3.2.2.1 Mathematical Model of MR Damper

In order to implement the behavior of the MR damper numerically so that the control forces can be predicted accurately, many mathematical models were developed by researchers [64]. In these models, the nonlinearity properties of the damper were modelled by defining differential functions corresponding to fluid properties, current, and force, each with others. For more details about the development of mathematical models for magnetorheological dampers, refer to [64].

In this study, the modified Bouc–Wen model, which is widely used in the literature [72] because of its accurate prediction of the control forces, is utilized (see Figure 3.6).

The force of MR damper is traced by the sum of the forces generated by the original Bouc–Wen model and the nominal damper force due to the accumulator, which is expressed as a fictitious stiffness (k_1). The force traced by the original Bouc–Wen model is equal to a dashpot force ($c_1\dot{y}$) to include the response roll off of the MR damper when a small velocity is applied, the phenomena observed in the experimental results.

The mathematical expression for the model is given by the following differential equations [73]:

$$\begin{aligned} f &= \alpha z + c_o (\dot{x} - \dot{y}) + k_o (x - y) + k_1 (x - x_o), \\ \dot{z} &= -\gamma |\dot{x} - \dot{y}| z |z|^{n-1} - \beta (\dot{x} - \dot{y}) |z|^n + A (\dot{x} - \dot{y}), \\ \dot{y} &= \frac{1}{(c_o + c_1)} \{ \alpha z + c_o \dot{x} + k_o (x - y) \} \end{aligned} \quad \text{Eq. (3. 1)}$$

k_1 is the accumulator stiffness, c_o is the viscous damping observed at larger velocities, c_1 is the dashpot which is included in the model to introduce the nonlinear roll-off in the force-velocity loops[73], k_o is presented to control the stiffness at large velocities, whereas, x_o is the initial displacement of spring k_1 related to nominal force due to the accumulator, γ, β and A are coefficients related to hysteresis behavior of MR damper by which the MR model response can easily be adjusted to represent the actual response accurately.

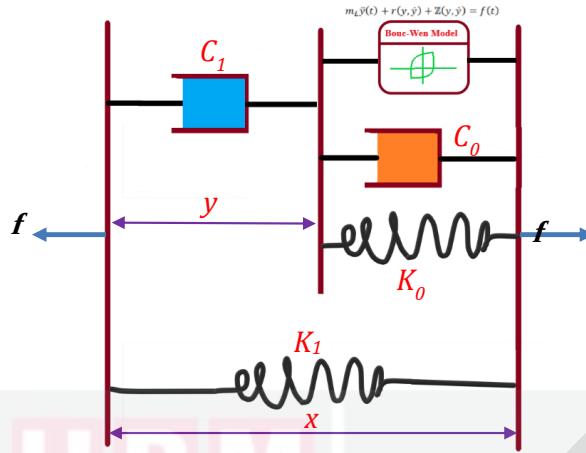


Figure 3.6: A schematic for the employed mechanical model of the MR damper

The MR behaviour under the effect of the magnetic field fluctuating is related to the MR fluid yield stress and the viscous damping constants which found to vary linearly with the change of driving voltage or current [71]. Accordingly, the parameters α , c_1 and c_o are related to the command voltage by the following equations (3.2-3.4) [73]:

$$\alpha = \alpha(u) = \alpha_a + \alpha_b u \quad \text{Eq. (3. 2)}$$

$$c_1 = c_1(u) = c_{1a} + c_{1b} u \quad \text{Eq. (3. 3)}$$

$$c_o = c_o(u) = c_{oa} + c_{ob} u \quad \text{Eq. (3. 4)}$$

(u) is a parameter reflecting the dynamics involved in the MR fluid reaching the rheological equilibrium and in driving the electromagnet in the MR damper. (u) is given by a first order filter expression (Eq. (3. 5)), where (v) is the commanded voltage by the current driver.

$$\dot{u} = -\eta(u - v) \quad \text{Eq. (3. 5)}$$

The conventional method to derive the above parameters is to run a constraint optimization and simulate the model with optimized values. Then, a comparison between the hysteretic curves for the experimental test and the numerical model has to be conducted to evaluate the model. However, in this study, the parameters used in [74] were employed, and the mathematical model was formulated using MATLAB SIMULINK Software [70]. Table 3.4 and Figure 3.7 show the values of the predefined MR model parameters and schematic for SIMULINK graphical programming of the modified Bouc-wen model, respectively.

To verify the model, a sine wave displacement of 0.015 m amplitude and a frequency of 2.5 Hz is simulated to excite the damper, then the hysteretic curves for the both passive-on and passive-off states were constructed, Figure 3.8) shows the hysteretic curves which are observed to match very well to what is presented in literature [74].

Table 3.4: Parameters for MR damper model (1500 N force capacity) [74]

<i>Parameter</i>	<i>Value</i>	<i>Parameter</i>	<i>Value</i>
c_{0a}	21.0 N s cm^{-1}	c_{1a}	283 N s cm^{-1}
c_{0b}	3.50 N s cm^{-1}	k_0	46.9 N cm^{-1}
	v^{-1}		
α_a	140 N cm^{-1}	k_1	5 N cm^{-1}
α_b	$695 \text{ N cm}^{-1} v^{-1}$	x_0	14.3 cm
c_{1b}	$2.95 \text{ N s cm}^{-1} v^{-1}$	γ	363 cm^{-2}
A	301	β	363 cm^{-2}
η	190 s^{-1}	n	2

3.2.2.2 The Analytical Model of MR Damper for Wind-induced Structure

Since the considered structure for the wind load case is a full-scale structure, the mathematical model of a full-scale MR damper of 1000 kN control force capacity is utilized. Following [75] and [76], the Bouc-Wen model parameters stated in Table 3.5 are employed.

The simplified form of Bouc-Wen model (phenomenological model) is used here, by which, the control force can be predicted accurately by the governing differential equations shown below [77]:

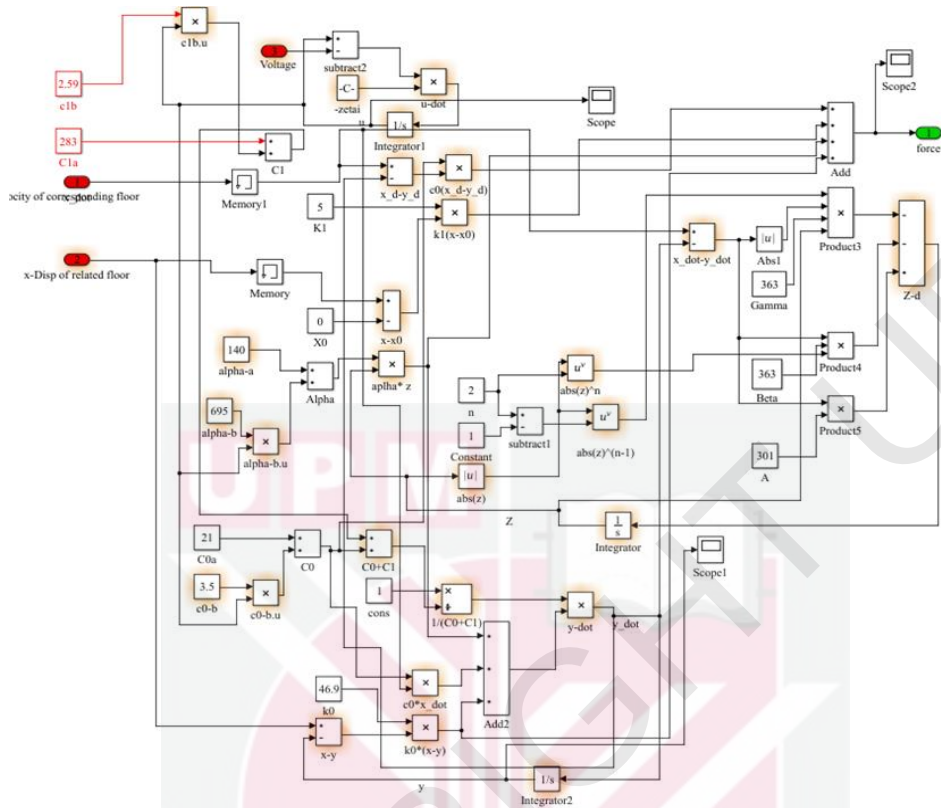


Figure 3.7: Bouc-Wen model formulation by SIMUINK graphical programming tool

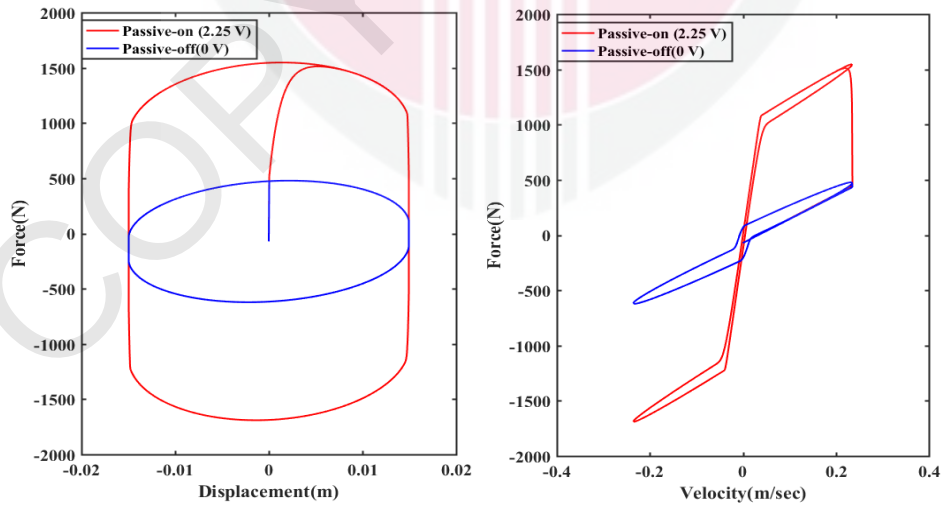


Figure 3.8: The simulated hysteretic curves for the mr model (force- displacement and force -velocity)

$$f = \alpha z + c_0 \dot{X} \quad \text{Eq. (3.6)}$$

$$\dot{z} = -\gamma |\dot{X}| z |\dot{z}|^{n-1} - \beta \dot{X} |z|^n + A \dot{X} \quad \text{Eq. (3.7)}$$

Same relations in Eq. (3.2-3.4) were employed to implement the driver current to the model. Moreover, the first filter in Eq. (3.7) was also utilized to trace MR dynamics.

Table 3.5: Parameters for the Bouc-Wen Model (1000 kN force capacity) [76]

<i>Parameter</i>	<i>Value</i>	<i>Parameter</i>	<i>Value</i>
c_{oa}	4.40 N s cm^{-1}	A	1.2
c_{ob}	$44.0 \text{ N s cm}^{-1} \text{ v}^{-1}$	η	50 s^{-1}
α_a	$1.0872e5 \text{ N cm}^{-1}$	γ	3 cm^{-2}
α_b	$4.9616e5 \text{ N cm}^{-1} \text{ v}^{-1}$	β	3 cm^{-2}
		n	1

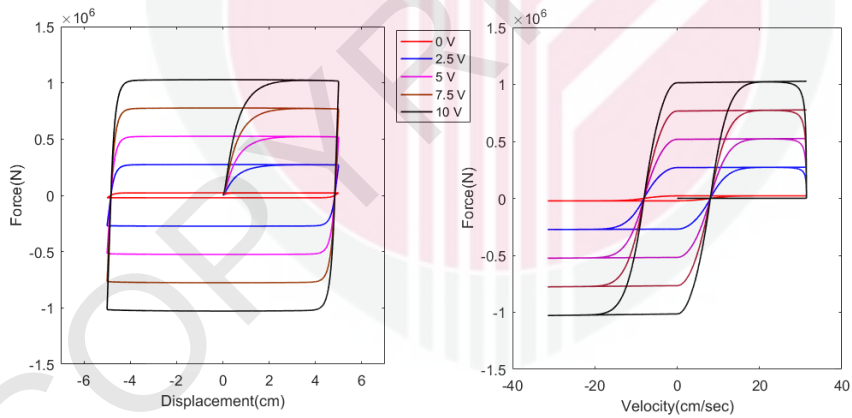
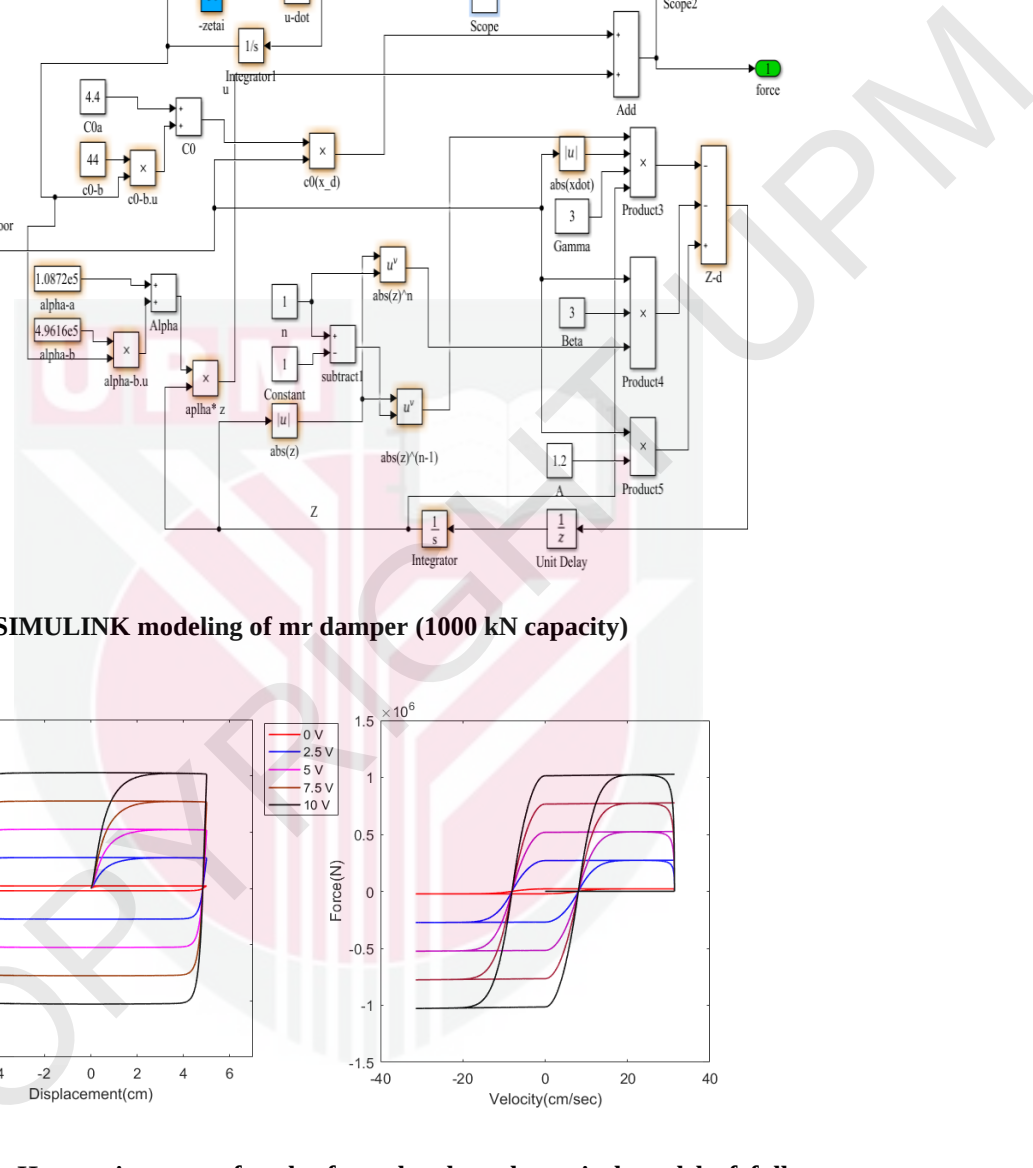
Using MATLAB & SIMULINK, the abovementioned formulations were modeled. The hysteretic curves for the MR damper subjected to a sinewave displacement of 5 cm amplitude and a 1 Hz frequency and for different values of driver voltage (V=0, 2.5, 5, 7.5 and 10) were plotted and compared with reference literature, showing that the model is identical to those used in [75], [76].

Figure 3.9 and Figure 3.10 are showing the SIMULINK version of MR model and the hysteretic curves, respectively.

3.2.3 Multi-Verse Optimization (MVO)

The Multi-Verse theory is a recent and well-known theory in physics [57]. The concept behind this theory is that more than one big bang had been happened. Each big bang is responsible for forming a universe, so there is more than one universe. The universes exchange objects with each other; however, a different law for each one is expected.

S. Mirjalili et al. [56] proposed a new multi verse-based optimization algorithm (MVO). It is inspired by the interaction of multiple universes via white holes, black holes, and worm holes. According to this theory, objects are transferred from a universe through a tunnel from a white hole to a black hole.



Also, worm holes can transport objects from one object of a universe to another without a need for a white or black hole, Figure 3.11. This algorithm can be classified as evolutionary algorithm under stochastic approach of optimization.

The main difference between the Genetic Algorithm (GA) and MVO is that cross over in GA happen for parts of parents and new generation are generated from only two parents of selected parents, while MVO allows any solution to contribute in the creation of new solutions. In addition, MVO has elitism feature and preserve the best solution obtained so far. This means MVO has improved exploration and exploitation mechanism. For insight information, reader can refer to [45].

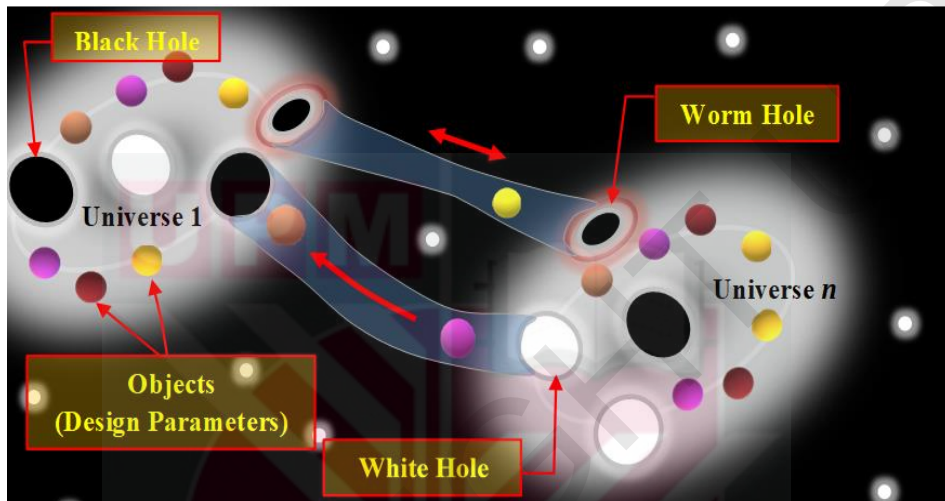


Figure 3.11: Inspiration of MVO

In MVO, each universe is a solution, and each design variable is an object in the universe. Wormholes are considered to ensure exploitation by allowing objects to travel instantly in each universe and even between different universes. Each solution (universe) has an inflation rate (fitness function) assigned to it. The iterations are termed as time since it is a common term in multi-verse theory and cosmology.

MVO is running according to the following rules:

- The higher inflation rate, the higher probability of having a white hole (existence of universe / solution).
- The higher inflation rate, the lower probability of having black holes (lower probability of abrupt changing in variables/ objects).
- Universes with higher inflation rate tend to send objects through white holes (travel of good variable's values to the solutions with bad fitness value).
- Universes with lower inflation rate tend to receive more objects through black holes.
- The objects in all universes may face random movement towards the best universe via wormholes regardless of the inflation rate (random improvement in all universes to balance between exploration and exploitation).

3.2.3.1 Mathematical Expression for MVO

In order to mathematically model the concept of objects' exchange between universes, the authors [57] utilized a roulette wheel mechanism. This technique selects a random solution(universe) to have a white hole. The selection process is done after sorting the universes according to their normalized inflation rates, so that for minimization problems, the lower the inflation rate, the higher probability of sending objects through white/black hole tunnels. Although Exploration can be guaranteed using this mechanism, exploitation is not violated because of the existence of wormholes in each universe which ensure the transporting of objects between universes randomly without consideration of inflation rates. Furthermore, the authors suggested that wormhole tunnels are always set up between a universe and the best universe formed so far (a universe with a high inflation rate). This is to ensure local changes for each universe and consequently increase the probability of improving its inflation rate.

Abovementioned strategy is expressed mathematically as follows [57]:

$$X_i^j = \begin{cases} \begin{cases} X_j + TDR \times ((ub_j - lb_j) \times r_4 + lb_j) & r_3 < 0.5 \\ X_j - TDR \times ((ub_j - lb_j) \times r_4 + lb_j) & r_3 \geq 0.5 \end{cases} & r_2 < WEP \\ X_i^j & r_2 \geq WEP \end{cases} \quad \text{Eq. (3. 8)}$$

X_j refers to the j th parameter of the best universe. TDR and WEP are a coefficient, ub_j and lb_j are the upper bound and lower bound for the j th parameter, respectively. r_2 , r_3 , r_4 are random numbers in $[0,1]$ interval, X_i^j is the j^{th} parameter for the i^{th} universe.

The most important coefficients are the Travelling Distance Ratio (TDR) and the Wormhole Existence Probability (WEP). The former is the distance rate to transport objects around the best universe; this value changes increasingly over the iterations to ensure precise exploitation around the best universe. On the contrary, the WEP coefficient is presented to ensure exploration over the advance of the optimization process.

Although WEP and TDR can be assumed constants over the optimization process, it is recommended to use the following relations to update these coefficients adaptively over the iterations [57]:

$$WEP = min + l \times \left(\frac{max - min}{L} \right) \quad \text{Eq. (3.9)}$$

$$TDR = 1 - \left(\frac{L^{1/p}}{L^{1/p}} \right) \quad \text{Eq. (3.10)}$$

Where (*min*) is minimum value of WEP, (*max*) is the maximum value of WEP, *l* is the current iteration, *L* is the maximum iterations. *p* is the exploitation/local search accuracy, the higher *p* the higher accuracy of local search.

In this study the values of 0.2, 1, and 6 are used for *min*, *max* and *p*, respectively.

3.2.3.2 Multi Objective Multi Verse Optimization (MOMVO)

The multi-objective version of the Multi-Verse Optimization algorithm, presented by Mirjalili S. et al. (2017) [56], was employed in this research. It is based on the original version of MVO; however, an archive with updating methodology was developed to maintain and improve the coverage of Pareto optimal solutions.

In this algorithm, like other population-based stochastic algorithms with multi-objective functions, the concept of Pareto optimality is utilized. The best solution is selected by employing the Pareto optimal dominance operator to compare different optimal solutions for different objective functions.

The archive technique utilizes storage for Pareto optimal solutions obtained so far and improves this set with optimization progress. Although the search mechanism is the same in MVO, the best solutions obtained so far (white holes) and the worm tunnels must be chosen from the archive due to the existence of multi non dominated solutions for multiple objectives.

A leader selection mechanism has been employed so that the crowding distance between each solution in the archive is first selected then the count of neighborhoods solutions is calculated as a measure of convergence or diversity.

To improve the distribution of solutions in the archive across all objectives, MOMVO employed the roulette wheel method to select the best solution from the less populated regions of the archive (solutions with a low inflation rate). The following equation is used to express the mechanism above mathematically [56]:

$$p_i = \frac{c}{N_i} \quad \text{Eq. (3.11)}$$

Where c is constant and should be more than 1, N_i is the number of solutions around the i th solution. This would improve the probability of the less populated solutions to contribute to the improvement of others.

To guarantee that the archive is not getting full during the progress of the optimization process, the undesirable solutions, those with many neighborhood solutions, are thrown out of the archive using the inverse of the previous equation (Eq. (3.9)) [56]. So that:

$$p'_i = \frac{N_i}{c} \quad \text{Eq.(3.12)}$$

Where c and N_i are defined as stated in Eq. (3. 9), c is maintained as constant with a value more than one, however, in this study a constant of one was used.

MOMVO is complying with Multi Objectives Particle Swarm Optimization (MOPSO); both use the following rules in comparing and adding solutions to the archive. These rules can be summarized as follows:

- When a new solution dominates any solutions in the archive, the dominated solution must be replaced by the new one immediately.
- If a new solution does not dominate a solution in the archive, it should be discarded and not allowed to enter the archive.
- If a solution is non-dominated with respect to all solutions in the archive, it should be added to the archive.
- If the archive is full, an undesired solution should be deleted, and the new non-dominated solution should enter the archive.

The abovementioned updating rules have been followed in this study. However, it is found that in the case of a real structural problem and when two subsequent solutions are identical (which is highly probable to happen when the numerical simulation is used), the archive has been left without any solution, which leads to cease the optimization process at all.

To solve this problem, the UpdateArchive function of the source code was modified, and then the optimization algorithm was tested before implementing it in the proposed methodology.

The main difference between the MOMVO algorithm and the Non-dominated Sorted Genetic Algorithm (NSGA-II) is that the former employs an archive which reduces the probability of damaging the non-dominated solutions with the progress of the optimization. Contrarily, the latter uses the non-domination level to choose the best

solution. Although this mechanism is good in enforcing exploration, it may violate other proper solutions during the optimization.

3.2.4 Objective Functions

In this work the superiority of MOMVO algorithm in carrying out multi-objective functions is employed by defining below objectives functions:

$$\begin{aligned} \text{Minimize: } f_1 &= \frac{1}{n} \sum_{j=1}^n \max(|\text{drift}_i(t)|) \\ f_2 &= \frac{1}{n} \sum_{i=1}^n \max(|\text{acc}_i(t)|), \\ i &= 1, 2, 3, \dots, n \quad t = 1, 2, 3, \dots, t_{\max}, \end{aligned} \quad \text{Eq.(3.13)}$$

Where f_1, f_2 is the proposed objective functions, i is the i^{th} story, $\text{drift}_i(t)$ and $\text{acc}_i(t)$ are the corresponding inter story drift and absolute acceleration at time (t) respectively.

3.2.4.1 Constraints and Penalty Function

One inequality constraint was defined for each objective function, is simply defined as:

$$\begin{aligned} f_1 &< \frac{1}{n \times m} \sum_{j=1}^m \sum_{i=0}^n \max(|\text{drift}_{i_o}(t)|) \\ f_2 &< \frac{1}{n \times m} \sum_{j=1}^m \sum_{i=0}^n \max(|\text{acc}_{i_o}(t)|), \end{aligned} \quad \text{Eq. (3.14)}$$

$\text{drift}_{i_o}(t)$ and $\text{acc}_{i_o}(t)$ are the uncontrolled story drift and story acceleration, respectively, j is corresponding earthquake or load component.

To penalize undesired universe that does not meet the constraints, following equation were employed:

$$f(r) = f(r) + \lambda^2 * \psi \quad \text{Eq. (3.15)}$$

Where $f(r)$ is the r^{th} objective function, λ is penalty constant ($= 10^{15}$), ψ is inequality function returning 0 when the constraint is confirmed and 1 when the constraint is violated.

3.2.5 Reference Control Strategies

For the purposes of comparison, two well-known semi-active vibration control strategies, Clipped Optimal (CO) and Modified quasi Bang-Bang (MBB), were utilized. These two algorithms are briefly described as follows:

3.2.5.1 Clipped Optimal

One of the most well-known semi-active vibration control algorithms is the Clipped Optimal (CO) algorithm, which was presented by Dyke et al. [73]. This algorithm is based on the optimal control force produced by a linear optimal controller (such as LQR or LQG). The CO algorithm commands the current driver of the MR damper with the desired command voltage in real-time, depending on the response and control force feedback signals which can be expressed as follows:

$$\mathbf{f}_c = \mathbf{L}^{-1} \left\{ -\mathbf{K}_c(s) \mathbf{L} \left\{ \begin{Bmatrix} \mathbf{y} \\ \mathbf{f} \end{Bmatrix} \right\} \right\}, \quad \text{Eq. (3.16)}$$

Where $\mathbf{f}_c$ is the optimal control force, $\mathbf{L}\{\cdot\}$ is the Laplace transform, $\mathbf{K}_c$ is the optimal feedback gain, $\mathbf{y} = [\ddot{\mathbf{x}}_1, \ddot{\mathbf{x}}_2, \ddot{\mathbf{x}}_3, \mathbf{x}_1]$ are the vector of feedback floors' acceleration response and the first floor displacement, respectively. $\mathbf{f}$ is the feedback control force generated by MR damper.

The control law can be expressed as:

$$\mathbf{V}_i = \begin{cases} \mathbf{V}_{i-1}, & \mathbf{f} = \mathbf{f}_c \\ \mathbf{V}_{max}, & \mathbf{f} \leq \mathbf{f}_c \mid \text{sign}(\mathbf{f}) = \text{sign}(\mathbf{f}_c) \\ \mathbf{0}, & \text{other cases} \end{cases}, \quad \text{Eq.(3. 17)}$$

$\mathbf{V}_i$ is the instant commanding voltage.

In this paper, a Linear Quadratic Regulator (LQR) controller was utilized to obtain the optimal response gain. Following Dyke et al. [73], Only the top floor response was taken into consideration, therefore the Q matrix was set to zero except for Q33, which was set to 1. The optimal Q and R multipliers of 10^{17} and 1, respectively, were determined through a trial-and-error approach using the (LQR) function in MATLAB for the structure excited by the El Centro earthquake.

3.2.5.2 Modified Quasi-bang-bang

The Quasi Bang-Bang control algorithm relies on passive-off and passive-on control states as control commands based on the direction of building movement, either towards or away from its static equilibrium. To improve upon this approach, Aly [74] proposed a modified Quasi Bang-Bang control strategy for semi-active vibration control structural systems equipped with MR dampers. In contrast to the clipped optimal and Quasi Bang-Bang strategies, the Modified Bang-Bang (MBB) approach uses a range of commanding voltage between 0 and the maximum value based on the structural feedback response. This approach can be expressed as follows:

$$\alpha_c V_i = \begin{cases} \alpha_c V_{max}, & (\text{sign}(x) = 1, \text{sign}(\dot{x}) = 1) \\ \beta_c V_{max}, & (\text{sign}(x) = -1, \text{sign}(\dot{x}) = -1) \\ \gamma_c V_{max}, & (\text{sign}(x) = 1, \text{sign}(\dot{x}) = -1) \\ V_{max}, & \text{other cases} \end{cases}, \quad \text{Eq.(3. 18)}$$

, β_c , and γ_c are coefficients between 0 and 1. However, for the sake of comparison the value of 0, 0.11 and 0.4 are employed, respectively, [74].

3.2.6 Earthquake Excited Structure

In this study phase, the developed vibration control algorithm was applied to a benchmark structure of a three-story building subjected to far-field and near-field natural earthquakes.

3.2.6.1 Three-story Shear Building

For the sake of comparison, a three-story shear building structure is considered to evaluate the performance of the developed vibration control system under the effect of seismic load. The structure is a benchmark structural control problem [94] and has been used in previous studies at the Structural Dynamics and Control/Earthquake Engineering Laboratory (SDC/EEL) at the University of Notre Dame. The structure has been modelled using state space representation. The uncontrolled response of the structure, excited by the El-Centro 1948 earthquake, has been compared with reference [74] as a validation criterion before implementing the developed control systems. The structure specifications and other modeling assumptions are shown in the following subsections.

3.2.6.2 Structure Specifications

The structure used for the earthquake excitation problem is a scaled model of a prototype structure with a steel frame of 158 cm in height and 227 kg of total mass distributed evenly along the floors [71]. Figure 3.13 shows a schematic for the scaled model of the benchmark structure.

The structure matrices are shown below [71].

$$M = \begin{bmatrix} 98.3 & 0 & 0 \\ 0 & 98.3 & 0 \\ 0 & 0 & 98.3 \end{bmatrix} kg, \quad K = \begin{bmatrix} 12 & -6.84 & 0 \\ -6.84 & 13.7 & -6.84 \\ 0 & -6.84 & 6.84 \end{bmatrix} \times 10^5 \frac{N}{m}$$

,Eq. (3.19)

The considered structure is assumed to be subjected to three one-dimensional earthquake time history excitations, include of one far-field and two near-field earthquakes. Therefore, the following earthquake records applied to the three-story structure:

- i) El Centro earthquake, 1940 (PGA=0.348g (m/s²)): The N-S component recorded at the Imperial Valley Irrigation District substation in El Centro, California, during the Imperial Valley, California earthquake of May 18, 1940;

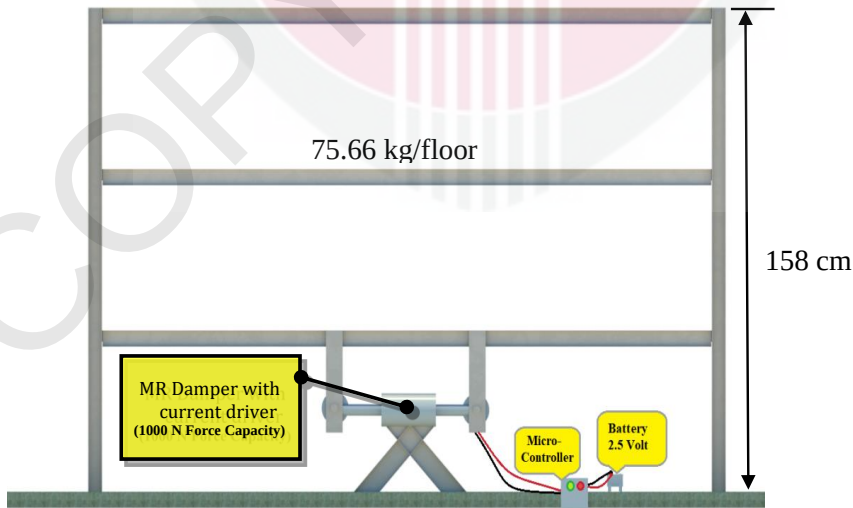


Figure 3.12: A schematic for the structure model

- ii) Kobe earthquake, 1995 (PGA=0.834g (m/s²)): The N-S component recorded at the Kobe Japanese Meteorological Agency (JMA) station during the Hyogoken Nanbu earthquake of January 17, 1995.
- iii) Northridge earthquake, 1994 (PGA=0.843g (m/s²)): The N-S component recorded at Sylmar County Hospital parking lot in Sylmar, California, during the Northridge, California earthquake of January 17, 1994.

Figure 3.13 shows the accelerations for the considered earthquakes.

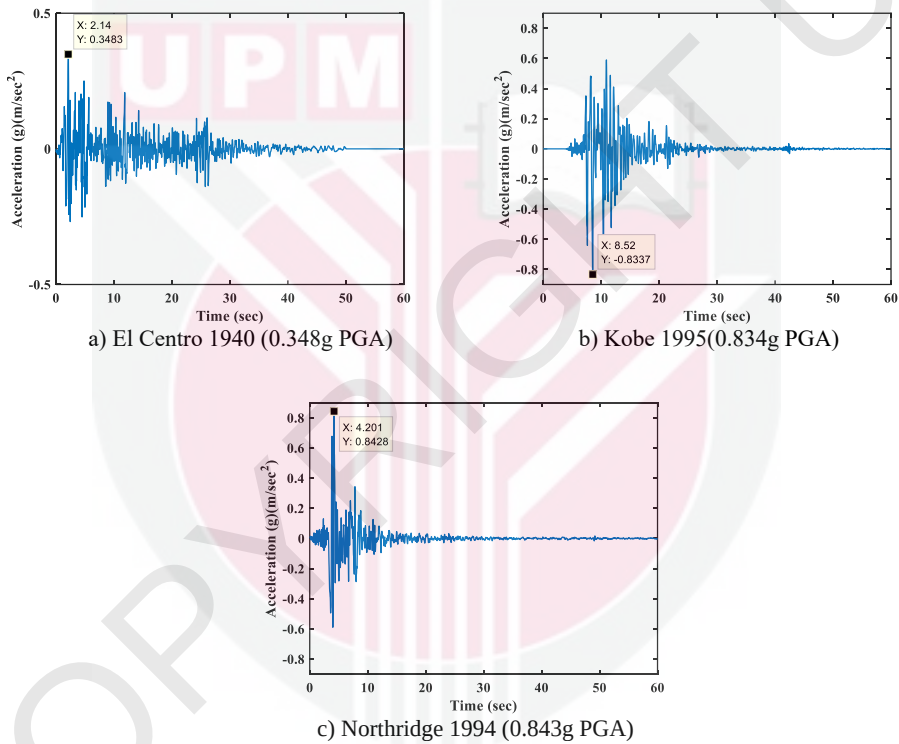


Figure 3.13: Historical earthquake accelograms

There is one MR damper assumed to be attached rigidly by chevron bracing frame between the ground and first floors so that damper velocity is equal to floor velocity.

3.2.6.3 Modeling of State Space System

The equation of motion for a structure subjected to ground motion is given by:

$$M\ddot{X} + C\dot{X} + KX = -Mg + \Gamma f \quad \text{Eq. (3.20)}$$

and Γ represents location matrix for the dampers. f is the control force.

The state space representation for the system is described by ordinary differential equation of LTI (Linear Time Invariant) dynamic system given by:

$$\begin{aligned} \dot{z} &= Az + Bf + E\ddot{g} \\ y &= Cz + Df \end{aligned} \quad \text{Eq. (3.21)}$$

Where z is the state vector; A , B , C , D , and E are state space matrices; $f = [f_1, f_2, f_3, \dots, f_n]^T$ is a vector of measured control forces; y is the measured output (in this study, measured states or outputs are: storey displacement, velocity and acceleration); and n is the number of degrees of freedom (number of storeys for one-dimensional structural model).

The State space matrices are given as below:

$$\begin{aligned} A &= \begin{bmatrix} 0_{n \times n} & I_{n \times n} \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, C = \begin{bmatrix} M^{-1}K & M^{-1}C \\ I_{n \times n} & 0_{n \times n} \\ 0_{n \times n} & I_{n \times n} \end{bmatrix} \\ B &= \begin{bmatrix} 0_{1 \times n} \\ M^{-1}\Gamma \end{bmatrix}, D = \begin{bmatrix} M^{-1}\Gamma \\ 0_{2n \times n} \end{bmatrix}, E = -\begin{bmatrix} 0_{1 \times n} \\ I_{1 \times n} \end{bmatrix} \end{aligned} \quad , \text{Eq. (3.22)}$$

The structure properties presented in literatures [65], [73], [78] were employed here, Eq. (3.20):

$$\begin{aligned} M &= \begin{bmatrix} 98.3 & 0 & 0 \\ 0 & 98.3 & 0 \\ 0 & 0 & 98.3 \end{bmatrix} \text{ kg}, \quad C = \begin{bmatrix} 175 & -50 & 0 \\ -50 & 100 & -50 \\ 0 & -50 & 50 \end{bmatrix} \text{ N.s/m} \\ K &= \begin{bmatrix} 12 & -6.84 & 0 \\ -6.84 & 13.7 & -6.84 \\ 0 & -6.84 & 6.84 \end{bmatrix} \times 10^5 \frac{\text{N}}{\text{m}}, \quad \Gamma = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \quad \Lambda = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \end{aligned} \quad , \text{Eq. (3.23)}$$

The damping matrix has been calculated using Rayleigh Method for the first two modes with a five percent damping ratio [79]. However, the values shown in equation, Eq. (3.20) are used for verifying purposes.

3.2.6.4 Optimal Controller by FLMVOC

The procedures presented in the previous sections (3.2.1) have been employed to get the optimal fuzzy logic controller and deploy it in the structural system. The formulated fuzzy logic controller has been trained with the proposed optimization method presented in section 3.2.3 under the effect of seismic loads (section 3.2.5.2). Then the optimal controller is selected among the Pareto optimal solutions. The Pareto optimum solutions and the optimization criteria are shown in Figure 3.14 and Table 3.6, respectively.

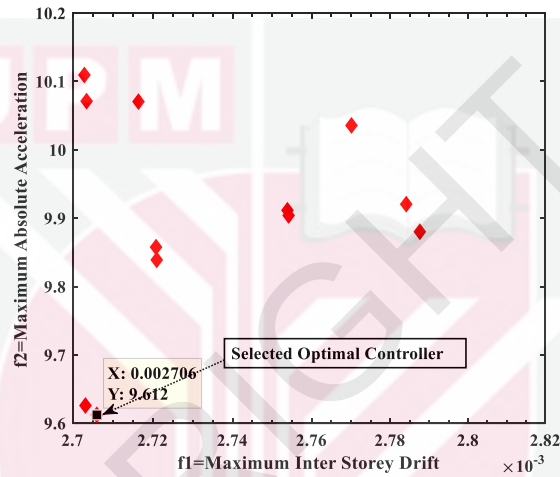


Figure 3.14: Pareto optimal solutions (fuzzy logic controllers) for earthquake excited structure

Table 3.6: Optimization parameters for the earthquake excited application

<i>Parameter</i>	<i>Value</i>
<i>Number of iterations</i>	20
<i>Number of Universes</i>	20
<i>Archive Size</i>	100
<i>Number of independent iterations</i>	5
<i>Objective functions</i>	2
<i>Number of design variables</i>	110

It is clear from the optimization results that there is no significant difference between the solutions over all iterations since there is a slight change in the values of the objective functions. This gives a good sense of the powerful performance of the proposed algorithm since it can produce a good solution after a few iterations. Base rules' weights and membership functions for the optimized controller are shown in Table 3.7.

Table 3.7: Base rules weights for the optimal fuzzy logic controller

<i>Drift</i>	<i>Acceleration</i>						
	<i>LN</i>	<i>N</i>	<i>SN</i>	<i>Z</i>	<i>SP</i>	<i>P</i>	<i>LP</i>
<i>LN</i>	MV 0.9373	MV 0.1615	HV 0.0087	MV 0.9589	MeV 0.9810	MeV 0.9810	LV 0.6237
<i>N</i>	MV 0.5152	HV 0.0027	NV 0.7539	NV 0.5092	MeV 1	MeV 0.8117	LV 0.5220
<i>SN</i>	NV 0.8128	NV 0.4435	NV 0.1685	MeV 0.1978	LV 0.6322	LV 0.0038	LV 0.7555
<i>Z</i>	MeV 0.6962	MeV 0.6840	LV 0.0870	LV 0	LV 0	LV 0.9426	LV 0.0208
<i>SP</i>	NV 0.2151	MeV 0.3215	LV 0.3353	LV 0.4588	MeV 0.7936	NV 0.3565	NV 0.3510
<i>P</i>	MeV 0.5647	NV 0.0495	NV 0.7531	NV 0.7411	HV 0.4303	HV 0.0666	MV 0
<i>LP</i>	NV 0.8835	NV 0.8650	HV 0.1518	HV 0.4065	HV 0.6866	MV 0.1245	MV 0.6994

3.2.7 Numerical Application for Wind Excited Control System

A 60-story reinforced concrete building, known as the CAARC building (Melbourne, 1980), was selected to be simulated in the full degree of freedom as an application to evaluate the robustness of the developed control algorithm. The following subsections show the structural properties and simulation details.

3.2.7.1 Structure Properties

The selected building is well known as the CAARC building (Melbourne, 1980) [80]. The building is 45.72 m in width, 30.48 m in depth, and 182.88 m in height.

The structure consists of seven by five bays. It is a moment-resisting system and contains 2880 columns and 4920 beams. its floors are assumed to be rigid diaphragms.

The building is considered stationed in a hurricane-prone area near Melbourne Beach, Florida. The orientation angle of the building is 270° clockwise from the north, i.e., the front façade faces the north. Figure 3.15 shows the plan and 3D views of the

considered structure. The structural members' properties are shown in Table 3.8, the concrete density of 2500 kg/m³ was used, and compression strength of 60 MPa was assumed.

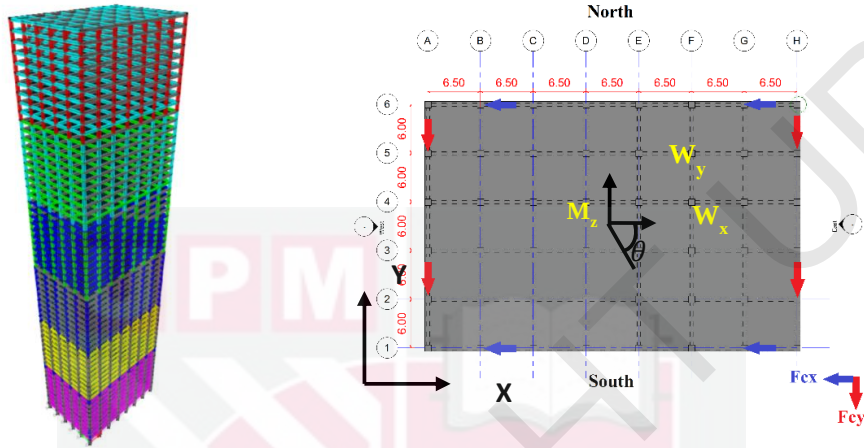


Figure 3.15: The plan and 3D view for the wind excited structure

The analysis is conducted using ETABS software by utilizing EATBS oAPI (Open Application Programming Interface) [81],[82] during the optimization process and later on during full simulation for the controlled structural system with optimal controllers.

Linear Modal Time history analysis is employed to simulate the structure at each time step. The structural analysis has been performed by employing only the first six modes of vibration to decrease the simulation time. The higher vibration modes, however, have been excluded since they have not participated effectively in the structural response. A damping ratio of 2% has been adopted for all six modes [80]. Table 3.9 and Figure 3.16 show the modal properties of the considered structure.

A ramp time history function has been defined to trace the dynamic action of the applied load at each time step. A pulse width equal to the load time sample is utilized. Then, the ramp function is assigned to the modal time-history load case for all dynamic load components.

Table 3.8: Cross-sectional properties for the 60-story building

<i>Member</i>	<i>Cross Section</i>	<i>Story</i>
<i>Corner column</i>	750 × 750	51st ~60 th
	750 × 750	41st ~50th
	800 × 800	31st ~40th
	850 × 850	21st ~30th
	900 × 900	11th ~20th
	1100 × 1100	1st ~10th
<i>Non-corner column</i>	750 × 750	51st ~60 th
	750 × 750	41st ~50th
	800 × 800	31st ~40th
	850 × 850	21st ~30th
	900 × 900	11th ~20th
	1100 × 1100	1st ~10th
<i>Exterior Beams</i>	400 × 700	51st ~60 th
	400 × 700	41st ~50th
	450 × 750	31st ~40th
	500 × 750	21st ~30th
	550 × 750	11th ~20th
	550 × 800	1st ~10 th
<i>Interior Beam</i>	400 × 700	51st ~60 th
	400 × 700	41st ~50th
	450 × 750	31st ~40th
	500 × 750	21st ~30th
	550 × 750	11th ~20th
	550 × 800	1st ~10 th

Table 3.9: Modal properties for the numerical model of the 60-story structure

<i>M ode</i>	<i>Peri od (sec)</i>	<i>Frequency (cycle/sec)</i>	<i>Circular Freq. (rad/sec)</i>	<i>Eigenvalue (rad²/sec²)</i>
1	5.228	0.191	1.201	1.4442
2	4.125	0.242	1.5232	2.3203
3	2.414	0.414	2.6024	6.7725
4	1.359	0.736	4.624	21.3838
5	1.212	0.825	5.1848	26.8817
6	0.917	1.09	6.851	46.9358

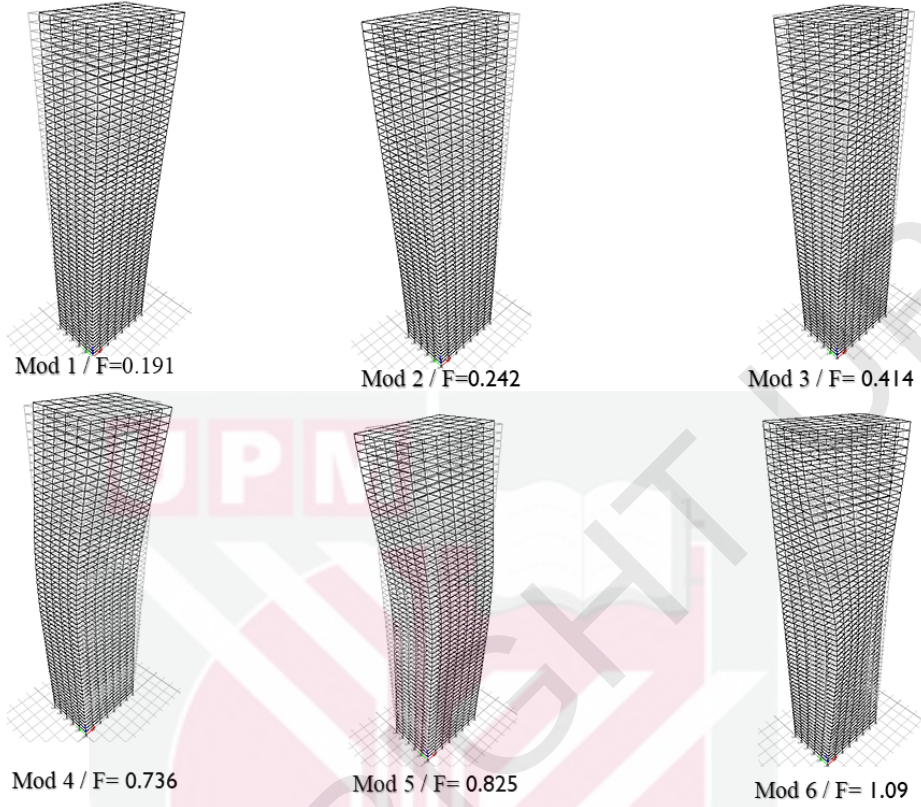


Figure 3.16: First six modes shapes for the 60 story building

3.2.7.2 Wind Load Time History Records

The wind tunnel pressure coefficients from High Rise Database Assisted Design (HR-DAD) [84][80] were employed. The building is assumed to be located in a type C exposure area. The pressure coefficients were measured in wind tunnel tests at the Prato (Italy) Inter-University Research Centre on Building Aerodynamics and Wind Engineering (CRIAC IV-DIC) Boundary Layer Wind Tunnel.

The hourly mean speed at the top floor for the building model in the wind tunnel test was 23.2 m/s, a hurricane wind speed of 67.5 m/s for 1700 years MRI [85] has been assumed, and the wind load time history has been scaled using following formulas [85]:

$$\bar{V} = \bar{b} * \left(\frac{z}{10} \right)^{\bar{\alpha}} * V \quad \text{Eq. (3.24)}$$

Where V is the basic wind speed corresponds to a 50-year mean recurrence interval at 10 m aboveground and for exposure category C (or 3sec gust speed), $\bar{V}$ is mean hourly design wind speed, $\bar{Z}$ is effective structure height ($=0.6 \times \text{considered height}$), $\bar{b}$ is Gust factor 1/F at 10 m, $\bar{\alpha}$ is Power law exponent of mean wind speed profile.

The values used here are 110 m (0.6×182.88), 0.65 and 0.153 for $\bar{Z}$, $\bar{b}$ and $\bar{\alpha}$ respectively.

The scale factor is obtained using following formula [86]:

$$\left(\frac{U}{U_r}\right)^2 \quad \text{Eq. (3.25)}$$

Where U is the design mean wind speed at top floor and U_r is the reference hourly mean wind speed (i.e. 23.2 m/sec).

Bernoulli's equation for fluid was utilized to calculate the load from pressure coefficients after scaling, it is defined as follows:

$$P = C_p \times 0.5 \times \rho \times V^2 \times A_f \quad \text{Eq. (3.26)}$$

Where P is the wind load, C_p is the pressure coefficients, ρ is air mass density (1.25 kg/m^3) and A_f is the floor area.

Three components of wind load records, X-direction, Y-direction and rotational load, have been used during both optimization and evaluation stages. These records, including multi-attack angle wind load, have been applied to all building floors (i.e. $\theta_i = 0^\circ, 30^\circ, 40^\circ, 50^\circ, 60^\circ, 70^\circ, 80^\circ, \text{and } 90^\circ$), where i is the i^{th} floor. However, to avoid confusion, only the wind load for the top story and for $\theta = 90^\circ$, i.e. along wind case, was plotted and shown in Figure 3.17.

Since the wind pressure coefficients are calculated and corrected to be exerted on the centre of the floor [84], wind load components are also applied as a point load in the centre of the floor (diaphragm).

It is worth mentioning that the optimum number of dampers is not intended in this study. Hence, four dampers in each direction are assumed at selected points, Figure 3.15.

Since the proposed controller has been fed with a story drift as one of the controller inputs, story 42 has been selected to be the study floor as it is seen from the initial analysis that it has the maximum story drift for the considered vibration modes, Figure 3.18.

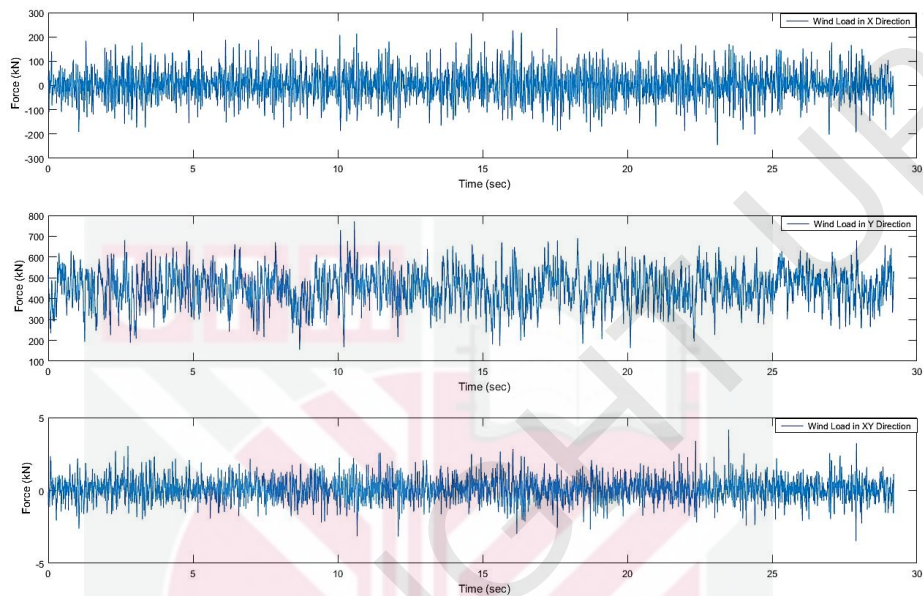


Figure 3.17: Along-wind time history load (60th story)

3.2.7.3 Optimal Controller for Wind-excited Structure

Following the previously stated procedures of the developed fuzzy logic multi-verse optimal control (FLMVOC) system (section 3.2), the optimization has been run by utilizing ETABS oAPI to integrate the different simulation environments of the controller and 3D structure; this is done by accessing a .NET dynamic link library form of API from MATLAB as .NET client.

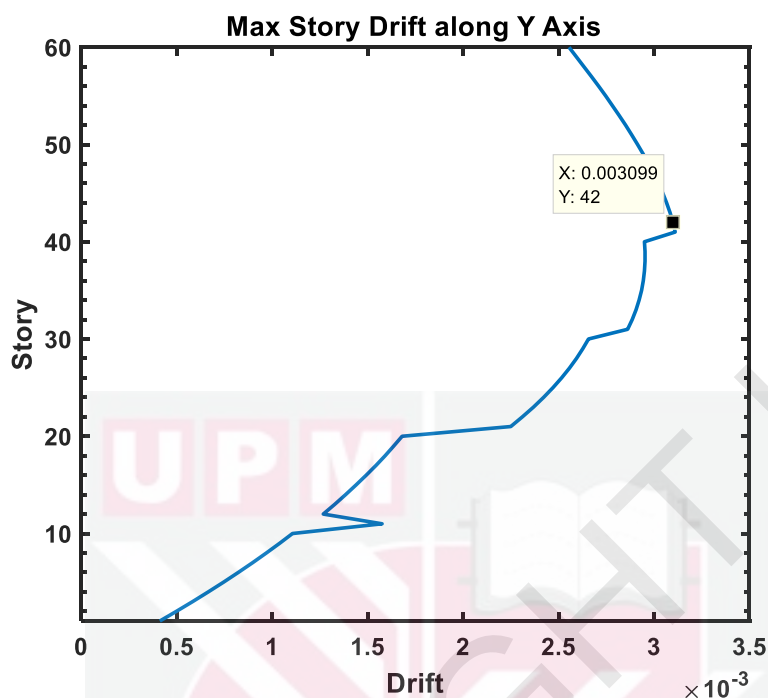


Figure 3.18: First mode maximum story drift

The developed fuzzy logic controller in section 3.2.1.3 has been implemented; however, in contrast to earthquake-excited structures, controlling the acceleration is a more critical design criterion in the wind-excited structure. Therefore, the fuzzy rules have been formulated to focus more on controlling acceleration by commanding a large control force when high values of structural acceleration response happen, regardless of the story drift values.

Figure 3.4 and Table 3.2 show the proposed membership functions and the base rules, respectively.

Because of the high computational power consumption of a 3D simulation, only 5-time steps were used during the optimization process. However, a set of fifty-time steps is employed to simulate the structure furnished with the optimal controllers. Table 3.10 shows the optimization parameters for the wind-excited problem.

The optimal controller, which has been obtained by the optimization process, is chosen amongst the Pareto optimal solutions, and then it is implemented at each control point in the concerned floor (section 3.3.2.2). After that, the simulation was done for the system excited by a complete set of wind load records (section 3.2.2.2). Figure 3.19 and Table 3.11 show the Pareto optimal solutions and the produced base rules' weights for the optimal controller, respectively.

Table 3.10: Optimization parameters for wind excited structural vibration control system

<i>Parameter</i>	<i>Value</i>
<i>Number of Iterations</i>	3
<i>Number of Universes</i>	20
<i>Archive Size</i>	100
<i>Number of independent iterations</i>	3
<i>Objective functions</i>	2
<i>Number of design variables</i>	110

Table 3.11: Base rules' weights for the optimal fl controller (wind excited structure)

<i>Drift</i>	<i>Acceleration</i>						
	<i>LN</i>	<i>N</i>	<i>SN</i>	<i>Z</i>	<i>SP</i>	<i>P</i>	<i>LP</i>
<i>LN</i>	MV 0.9779	MV 0.4368	NV 0.0953	NV 0.2091	NV 0.4312	MV 0.3361	MV 0.8540
<i>N</i>	NV 0.7619	NV 0.2062	MeV 0.2375	MeV 0.6143	MeV 0.0849	NV 0.7285	NV 0.0679
<i>SN</i>	MeV 0.1123	MeV 0.5440	LV 0.3119	LV 0.1821	LV 1	MeV 0	MeV 0.8085
<i>Z</i>	MeV 0	LV 0.3272	LV 0.8998	LV 0	LV 0.3272	LV 0.8008	MeV 0.1345
<i>SP</i>	MeV 0.5924	MeV 0.6038	LV 0.2261	LV 0.5417	LV 0.7350	MeV 0.7771	MeV 0.6261
<i>P</i>	NV 0.5085	NV 0	MeV 0.7191	MeV 0.1556	MeV 0.6628	NV 0.6543	NV 0.5387
<i>LP</i>	MV 0.1303	MV 0.9530	NV 0.5720	NV 0.9571	NV 0.6440	MV 0.8302	MV 0.5739

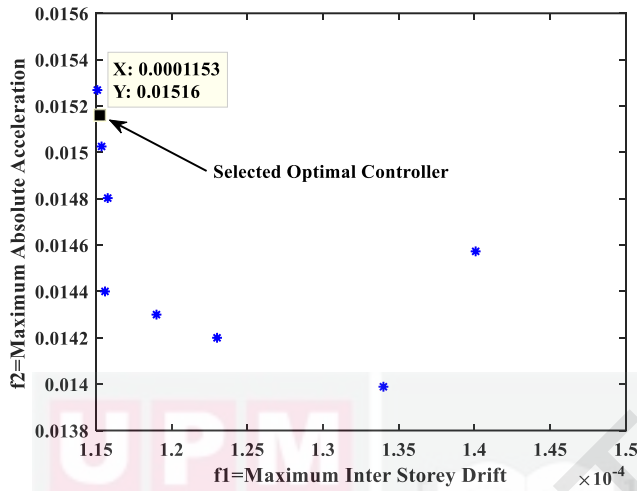


Figure 3.19: Pareto optimal FLC controllers for wind-excited structure

3.3 Online Fuzzy Logic Multi Verse Optimal Control Algorithm (Online-FLMVOC)

It revealed from the previous studies the limited capability of model-based algorithms in carrying the uncertainties in external excitations and structural properties since its parameters depend on the available data utilized at deriving phase. Although intelligent controllers such as fuzzy logic-based controllers are more robust than model-based controllers, their performance depends on offline training data, i.e., despite the real-time response of the control system, the controller's parameters are not changed in real-time. Therefore, this section illustrated a step by step the development of the novel Online-FLMVOC structural vibration control system.

The developed vibration control system hybridizes two main techniques; fuzzy logic inference systems [67] and multi-objective multiverse optimization algorithm [56]. The magnetorheological damper (MR) is deployed as a controllable vibration control device owing to its damping efficiency and low power consumption. The fuzzy base rules and the inputs and outputs membership functions for the fuzzy logic controller (FLC) were developed. The story displacement and absolute acceleration have been defined as the controller's inputs, while the commanding voltage for the MR damper has been defined as the controller's output. Then the analytical model for MR damper is formulated and integrated with the developed system. To launch the optimization process online in parallel with the vibration controlling job, an integrated simulation and evaluating environment has been developed by utilizing the MATLAB program and its Simulink and then linking it with a finite element package. To prevent the loss of the best controllers obtained so far with the progress of time, a saving memory has been employed, then sorting and selecting strategy for the real-time best FLC has been formulated.

The developed algorithm attempts to address the following problems: the first is the dependency of the optimal controller on the available training data, and the second is the limited capability of the optimal controllers to control a multi-component structural response.

To achieve that, the Online-FLMVOC is utilizing a controllers' memory (FISMemory) to save the initial and optimal controllers obtained so far.

The technique mentioned above allows the optimization process to run progressively along the structure's life; meanwhile, the structural vibration control system can perform in real-time using the best available fuzzy logic controllers (FLC) in FISMemory regardless of the optimization process.

At each time step, the best FLC is selected adaptively according to the developed selection strategy; at the same time, the selected FLC is utilized to initiate the subsequent time steps optimization employing fuzzy logic multiverse optimal control (FLMVOC) system (section 3.2).

To guarantee the reliability of the proposed algorithm to tackle the uncertainties in external excitation and structural response, the concept of a decentralized control system has been employed so that the structure's response in each direction is controlled independently. Moreover, the use of a decentralized system enables us to implement the linear time-invariant model of the control system instead of the 3D simulation, which is more reliable in real applications. Figure 3.20 shows a flow chart for the developed system.

The Online-FLMVOC can control the vibration through the following summarized steps:

- 1- Get the initial fuzzy logic controllers for a specified dynamic load record: this would be done by off-line training utilizing Fuzzy Logic Multiverse Optimal Control (FLMVOC) algorithm.
- 2- Save the optimal controllers from 1 in the FISMemory; it is worth noting that FIS memory is of limited size; in this application, we utilized a ten rooms memory.
- 3- Define the desired limits of structural response (i.e., allowable drift and acceleration).
- 4- Start the structure simulation:

❖ •At each time step:

- Assign initial controller from FIS memory
- Get the responses
- Evaluate which one of the responses is more critical than the other:

The evaluation is done according to a developed selection strategy, by which a comparison between the desired response value and the corresponding objective function is made.

- Choose the available optimal controller with a minimum value of the concerned response.
- Assign the selected Controller (i.e., from the previous step) to the dampers' fuzzy logic controllers by changing its parameters. This would be used to control the response in the next time step.
- Enter FLMVOC optimization algorithm: the optimization is carried out independently for the substructure (sub-control system).
- The optimization output from the previous step represents the optimal controllers for the specified subsequent time steps.
- Update the FIS memory by stimulating the updating technique of the Pareto optimal solutions in MOMVO algorithm.

❖ Repeat the previous procedure for the next time steps.

The following subsections demonstrate the above methodology in detail.

3.3.1 Formulation of Fuzzy Logic Inference System (FIS)

Following the procedures stated in section 3.2.1, a feedback fuzzy logic inference system is formulated by defining two inputs: story drift or story displacement and story absolute acceleration. System output is proposed to be the commanding voltage for the Magnetorheological (MR) damper. Membership functions for the inputs were assumed as trapezoidal functions, while the output was formulated using triangular membership functions. Each input has seven shape functions. However, only five membership functions were utilized to define the system output.

For more details about the formulation of the FIS, refer to section 3.2.1

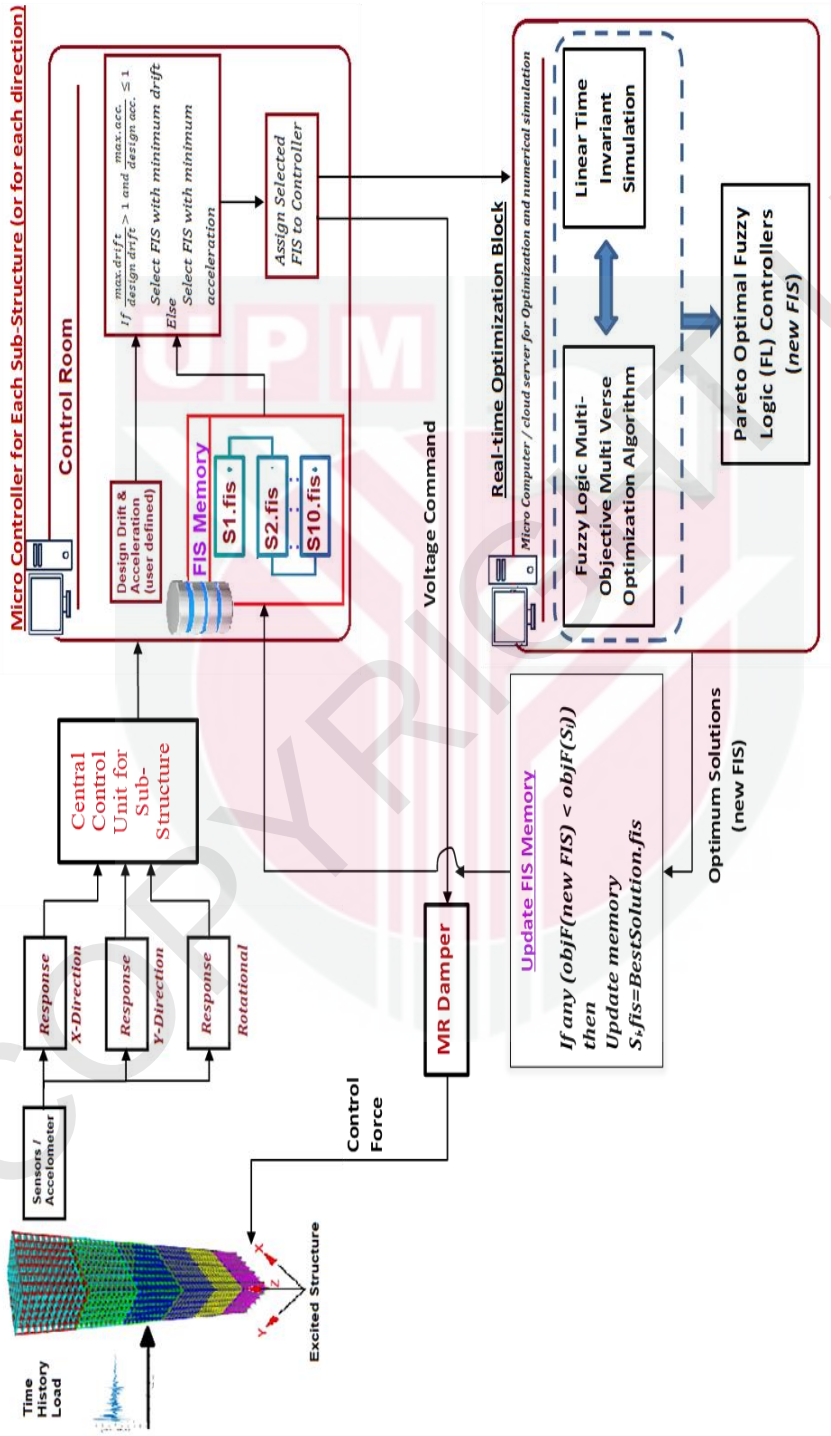


Figure 3.20: A flow chart for the developed online-FLMVOC system

3.3.2 Magnetorheological Damper (MR)

Magnetorheological Damper (MR) is employed as a semi-active vibration control device.

Following section 3.2.2, the analytical Bouc-Wen model and its parameters for earthquake and wind-excited structures were utilized to simulate the real-time control force generated by the MR damper. For insight information about developing the analytical model and the related tests, refer to section 3.3.2.

The developed pseudo code for the real-time optimization process is shown in Figure 3.21.

```
initialize the FIS memory with trial controllers
Specify memory size
for time = 1 to End_Time
    Choose the available optimum fuzzy logic controller According to the
    selection mechanism
    Assign Optimum Controller to the vibration control system
    Run the Simulation
    Get the real-time structural response
    Start The real-time optimization utilizing the MOMVO algorithm
        Define the optimization parameters
        Define the maximum number of independent iterations
        Define the maximum number of universes per iteration
        Define the maximum size of Solution Archive
        Define the maximum number of design variables(FIS membership
        functions and rules weights)
        Define the number of objective functions
        Start The Optimization for the forward steps
        Get the optimum FIS
    Update the FIS memory according to the updating technique
Next Time Step
```

Figure 3.21:Pseudo code for the real-time optimization

3.3.3 Real-time Optimization of the Fuzzy Logic Inference System

In this study phase, the real-time optimization of the developed vibration control system is based on the adjusted version of the multi-objective multi-verse optimization algorithm (MOMVO), (section 3.2.3). The following subsections highlight the most essential newly employed tools and parameters in developing the real-time optimization algorithm of the Fuzzy Logic Inference system.

3.3.3.1 Objective Function

The superiority of the MOMVO algorithm in carrying out multi-objective functions is employed by defining below objective functions:

$$\text{Minimize: } f_1 = \frac{1}{n \times m} \sum_{j=1}^m \frac{\sum_{i=1}^n \max(|drift_{i,j}(t)|)}{\max |drift_{i_o}(t)|}$$

$$f_2 = \frac{1}{n \times m} \sum_{j=1}^m \frac{\sum_{i=1}^n \max(|acc_{i,j}(t)|)}{(|acc_{i_o}(t)|)},$$

$$i=1,2,3,\dots,n \quad t=1,2,3,\dots,t_{\max}, \quad \text{Eq.(4.1)}$$

here f_1, f_2 is the proposed objective functions, i is the i^{th} story, $drift_i(t)$ and $acc_i(t)$ are the corresponding inter story drift and absolute acceleration at time (t) respectively, j is the corresponding earthquake or load component.

3.3.3.2 Constraints and Penalty Function

One inequality constraint was defined for each objective function which is defined as:

$$f_1 < \frac{1}{n \times m} \sum_{j=1}^m \sum_{i=0}^n \max(|drift_{i_o}(t)|)$$

$$f_2 < \frac{1}{n \times m} \sum_{j=1}^m \sum_{i=0}^n \max(|acc_{i_o}(t)|) \quad , \quad \text{Eq.(3.27)}$$

$drift_{i_o}(t)$ and $acc_{i_o}(t)$ are the uncontrolled story drift and story acceleration, respectively, j is corresponding earthquake or load component.

To penalize the undesired universe which does not meet the constraints, the following equation was defined:

$$f(r) = f(r) + \lambda^2 \times \psi \quad , \quad \text{Eq.(3.28)}$$

Where $f(r)$ is the r^{th} objective function, λ is the penalty constant ($= 10^{15}$), ψ is the inequality function returning zero when the constraint is confirmed and one when the constraint is violated.

3.3.3.3 Fuzzy Logic Controllers' Memory (FIS memory)

The principal concept of the developed Online-FLMVOC is to allow life optimization for the structural vibration control system. Online optimization is advantageous in enabling the capabilities of the developed vibration control system to produce better controllers by online training when the structural properties and external load are unpredictable.

However, the control action does not directly depend on the optimization phase; instead, the system employs the optimized controllers' parameters produced so far, regardless of the status of the optimization process.

At each time step, the developed system employs the best available controller data from the previous steps, meanwhile, the optimization for the specified forward time steps starts simultaneously utilizing time history records or stochastic methods of the load prediction.

The proposed algorithm is implemented in a decentralized system so that the training can be done by utilizing linear system simulation techniques, which commonly consume less processing time and, consequently, low computational power and a quick response system. A flow chart for the developed FIS memory and the selection mechanism are shown in Figure 3.22

3.3.3.4 Real-time Updating Technique

Many optimized controllers are supposed to be developed with the progress of the structure life; however, only the best specific number of the produced FIS will be kept in the FIS memory. The number of saved data sets (FISs) depends on the available memory space.

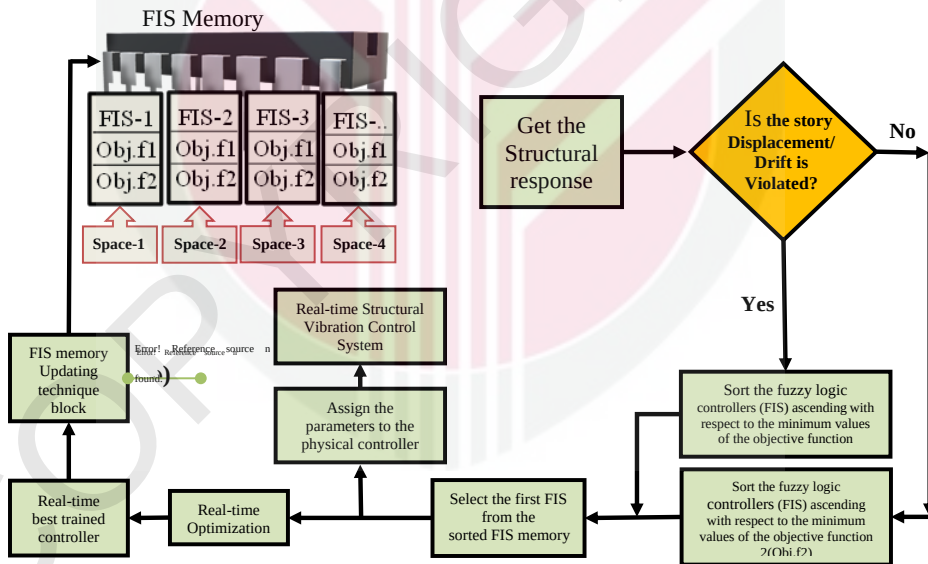


Figure 3.22: A flow chart for the developed FIS memory and the selection mechanism

The FIS data in last allocated space of the sorted memory is considered the most undesirable solution; hence, the data in the last slot is selected to be the only comparable controller.

To update the FIS memory with the real-time improved and optimized FIS, the new FIS is compared with the data set in the last slot (The FIS with maximum objective functions) of the sorted FIS memory according to the developed updating technique. As a result, only the new optimized FIS with the minimum objective functions is allowed to be saved in the FIS memory. Figure 3.23 shows a flow chart for the developed updating technique.

The developed algorithm has been carried out utilizing MATLAB and its SIMULINK toolbox [70].

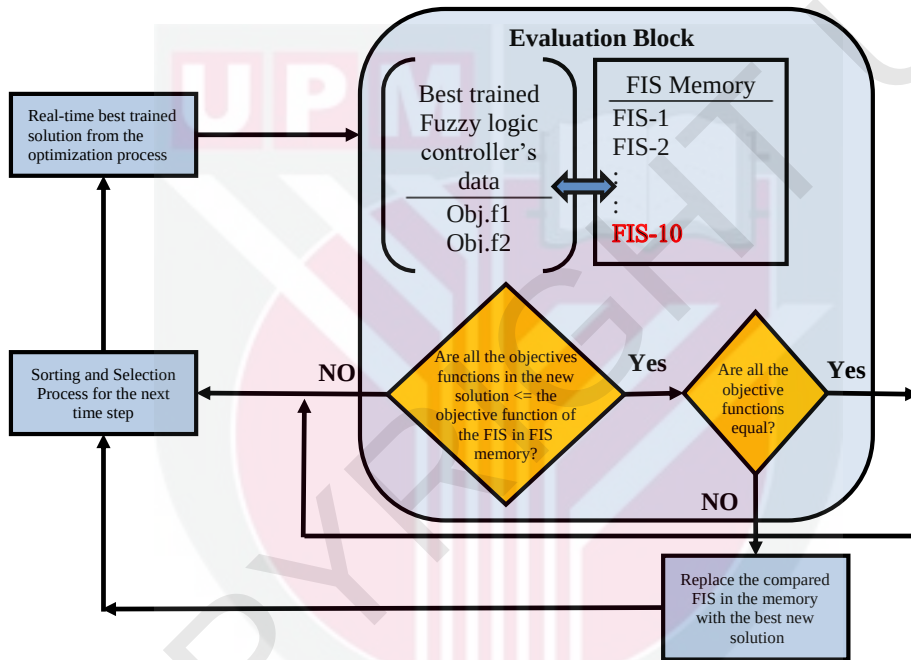


Figure 3.23: A flow chart for the developed FIS memory updating technique

3.3.4 Reference Control Strategies

For the purposes of comparison, two well-known semi-active vibration control strategies, Clipped Optimal (CO) and Modified quasi Bang-Bang (MBB), were utilized. These two algorithms are briefly described in section 3.2.5. In addition, FLMVOC algorithm, developed in section 3.2, is also utilized. The reader can refer to Tables 3.6 and 3.7 for the optimization parameters and the optimal fuzzy logic controller of offline-FLMVOC, respectively.

3.3.5 Earthquake Excited Structure

To assess the developed Online-FLMVOC algorithm, the structural vibration control system has been implemented in a three-story shear structure subjected to a real earthquake excitation. The following subsections present the specifications for the numerical applications in detail.

3.3.5.1 Three Story Benchmark Structure

A scaled model structure which has been used in the previous study (section 3.2.5) is employed. The reader can refer to section 3.2.5.1 for structure specifications.

3.3.5.2 Equation of Motion

The equation of motion for the earthquake-excited structure, the structure matrices, modelling assumptions, and the space state model for the considered structure are stated in section 3.2.5.2.

3.3.5.3 The Analytical Model for MR damper

The analytical model for the MR damper in sections 3.2.2.1 and 3.3.2 is employed.

3.3.5.4 Earthquakes Time History Records

To evaluate the reliability of the developed algorithm, the earthquake records in section 3.2.5.2 were employed. However, only two earthquakes are utilized: far-field and near-field earthquakes. Therefore, the three-story structure has been subjected to the following earthquake time history:

- I. Northridge earthquake, 1994 (PGA=0.843g (m/s²)): The N-S component recorded at Sylmar County Hospital parking lot in Sylmar, California, during the Northridge, California earthquake of January 17, 1994.
- II. El Centro earthquake, 1940 (PGA=0.348g (m/s²)): The N-S component recorded at the Imperial Valley Irrigation District substation in El Centro, California, during the Imperial Valley, California earthquake of May 18, 1940.

The sample time for the time history records is 0.02. However, to enable real-time optimization, the optimization process has been run every second period, in other words, every fifty steps.

To ensure reasonable simulation results, a sample time of 0.0001 and a period of 1.2 seconds were applied in SIMULINK so that the acceleration response does not exceed a scale factor of 1.5. Refer to Figure 3.13 for the earthquakes' acceleration plots.

3.3.5.5 Optimization Parameters

Since decreasing the optimization time is an essential factor in ensuring the reliability of the developed system, the optimization is carried out utilizing the minimum iterations and minimum population per iteration. Trial offline optimization was executed with different parameters then a comparison between the results was conducted. After that, the parameters that produce a good performance with minimum iterations were chosen. Table 3.12 shows the applied optimization parameters for the developed algorithm.

The optimization time spent per each load step is 2 minutes and 29 seconds. However, it is proposed that the optimization process will not cause extra delay to the control action since it responds independently.

Table 3.12: The optimization parameters for the earthquake load case (online-FLMVOC)

<i>Parameter</i>	<i>Value</i>
<i>Number of iterations</i>	<i>1</i>
<i>Number of Universes</i>	<i>20</i>
<i>Archive Size</i>	<i>50</i>
<i>Number of independent iterations</i>	<i>1</i>
<i>Objective functions</i>	<i>2</i>
<i>Number of design variables</i>	<i>110</i>

3.3.6 Wind-induced Structure

In this study phase, a benchmark 76-story building [46] was utilized to test the robustness of the developed vibration control system to the uncertainties in external excitations.

The building is a 306-m office tower proposed for the city of Melbourne, Australia [87]. The building has a square cross-section with a chamfer at the two opposite corners, as shown in Figure 3.24. It is sensitive to wind since its height-to-width ratio is 7.3.

The structural system for the building consists of a reinforced concrete core designed to stand for the lateral forces and a reinforced concrete frame of perimeter columns and spandrel beams. The majority of the reinforced concrete frame is to resist the gravity load.

In contrast to the literature, the building is modelled with a full degree of freedom under the effect of three wind load components.

The floors are assumed as rigid diaphragms then the real-time wind load components are applied as point loads in the centre of the diaphragm.

The control forces generated by the MR dampers were modelled as a point load at the selected control points (Figure 3.24). Four MR damper are deployed in each perpendicular directions (X-Direction and Y-Direction) at the concerned floor.

The modelling and analysing task were carried out utilizing ETABS software then the developed algorithm was applied by integrating MATLAB (and its SIMULINK) and ETABS employing the application programming interface (API) of ETABS [82]. The concrete density of 25 kN/m³ was used, and compression strength of 60 MPa was assumed.

Linear modal time history analysis was employed to simulate the structure at each time step. However, only the first fifteen modes of the structure vibration were involved in the analysis since they participated with over 90% of the actual mass in each orthogonal horizontal direction of response [83]. A 1% damping ratio was adopted for all considered modes [87]. Table 3.13 shows the characteristics of the considered modes of vibration.

In order to trace the dynamic action of the applied load at each time step, a ramp time history function was defined with a pulse width equal to the applied load sample time then the ramp function was assigned to the modal time history load case for all dynamic load components.

The vibration control system is assumed to be deployed on the 75th floor instead of the 76th floor since the 76th story is designed for mechanical equipment and is not occupied by people.

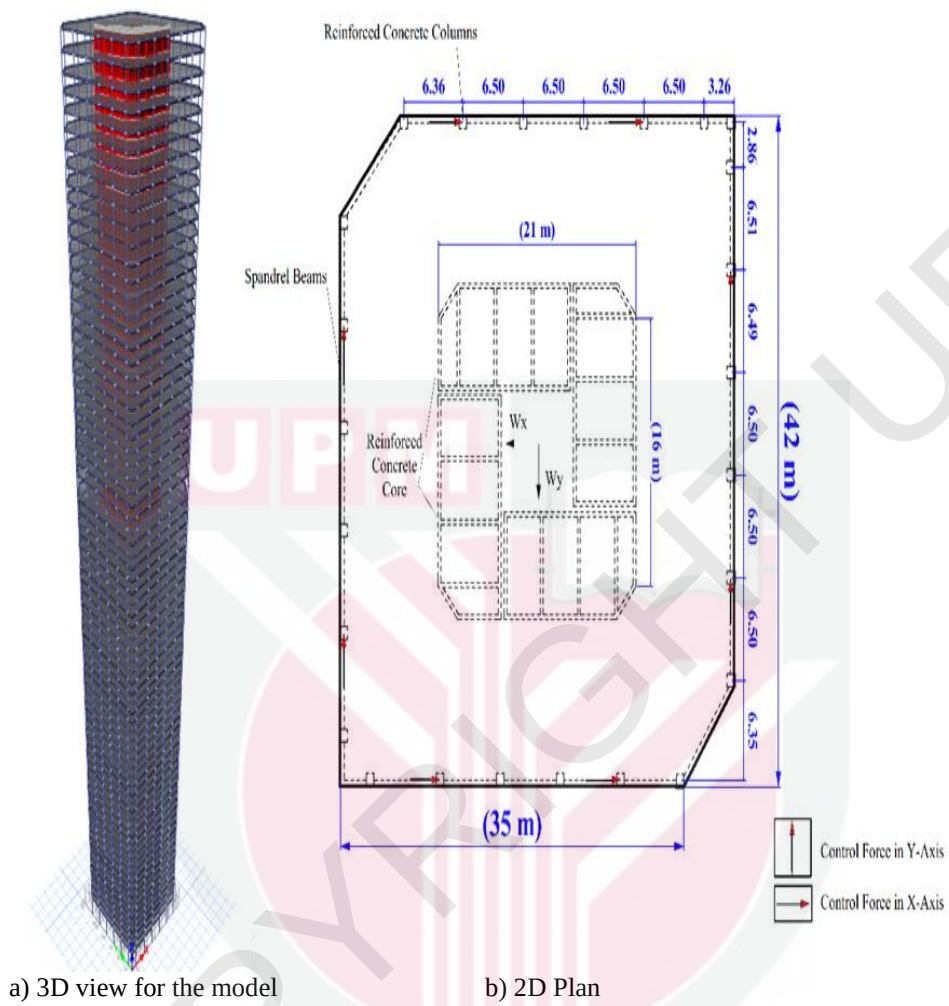


Figure 3.24: The considered 76-story benchmark building

Table 3.13: Modal analysis properties for 76-story building obtained by ETABS

MODE	PERIOD	FREQUENCY	CIRC.FREQ	EIGENVALUE	PART.RATIO	
	sec	cyc/sec	rad/sec	rad ² /sec ²	X-Dir	Y-Dir
1	7.084	0.141	0.887	0.7868	0.4028	0.2594
2	6.712	0.149	0.9361	0.8764	0.6638	0.6662
3	1.446	0.692	4.3452	18.8806	0.6638	0.6662
4	1.374	0.728	4.5727	20.9097	0.7659	0.7312
5	1.336	0.749	4.7037	22.1252	0.8297	0.8301
6	0.571	1.751	11.0005	121.0101	0.8665	0.8576
7	0.564	1.774	11.1439	124.1859	0.8937	0.8939
8	0.482	2.076	13.0439	170.1425	0.8937	0.8939
9	0.418	2.391	15.0217	225.652	0.8938	0.8939
10	0.323	3.095	19.4434	378.0444	0.9254	0.8962
11	0.213	4.704	29.5551	873.5044	0.9254	0.8967
12	0.191	5.232	32.8743	1080.7194	0.9254	0.9000
13	0.145	6.892	43.3063	1875.4374	0.9254	0.9018
14	0.104	9.608	60.3712	3644.6817	0.9255	0.9039
15	0.051	19.775	124.2524	15438.6536	0.9255	0.9056

3.3.6.1 Wind Load Time Histories

The adjusted Wind load time histories from NEES Metadata [88] were employed in this research. The wind forces acting on the building in along wind and across wind directions are obtained by the wind tunnel tests at the Department of Civil Engineering, the University of Sydney, Australia [89]. The wind return period is 10 years, a serviceability design mean wind speed of 47.23 m/s was assumed for the wind load generation [89]. However, in contrast to other research, both along-wind and across-wind loads were applied simultaneously on the structure, and the analysis was performed for a full degree of freedom. Only twenty time steps were utilized during the simulation because of computational power limitations. The time history load for the top floor is shown in Figure 3.25.

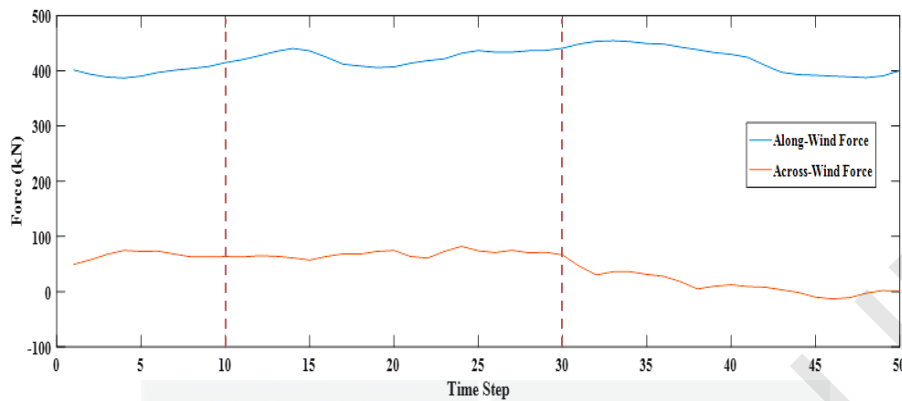


Figure 3.25: The considered wind time history forces exerted on the 75th floor

3.3.6.2 The Analytical Model for MR Damper

The Bouc-Wen model for a full-scale structure is employed. For more details, refer to section 3.2.2.

3.3.6.3 Optimization Parameters

In this study phase, the optimization parameters in section 4.3.2.4 were employed. However, only five universes were utilized to minimize the optimization process time and increase the probability of FIS memory updating.

Since the proposed optimization process will be done in parallel with the control action along the structure's life (Online-Optimization), the produced optimal Fuzzy Logic controller has been discussed in the next chapter.

3.4 Summary

This chapter presented the developments of two novel structural vibration control systems for the structures furnished with magnetorheological dampers (MR) to address the problems of this study.

The two systems utilized a Fuzzy Logic inference system and a multi-objective multi verse optimization algorithm in their formulations. Therefore, Fuzzy Logic controllers to control the MR dampers under the effect of seismic and wind loads have been developed through this chapter. Then the two developed optimization approaches, which are considered one of the two prominent factors that affect the performance of the developed vibration control system, have been demonstrated.

The structural load and MR damper properties for the system evaluation are also elaborated under the effect of varied intensity seismic load and multi-attack angle wind load.

The novelty of this work is recognized in the developed system, which is a first-of-its-kind hybrid system that integrates the Multi-Verse Optimizer (MVO) and Fuzzy Logic Controller (FLC). In addition, in FLMVOC, a single optimal Fuzzy Logic Controller has been developed, demonstrating the capability to effectively withstand various load patterns. Furthermore, Online-FLMVOC has been designed to perform optimally, even in the absence of specific data about the structure and load

The results and the related discussion in terms of the performance and robustness of the developed FLMVOC and Online-FLMVOC will be investigated in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSION

Following the methodology outlined in Chapter 3, this chapter presents and discusses the results for the developed systems. The chapter is divided into three sections. Section one presents the results of the developed Fuzzy Logic Multi Verse Optimal Control System (FLMVOC). This section is further divided into two subsections to discuss the performance and the robustness of the developed FLMVOC under the effects of earthquake and wind loads, respectively. Section two follows the same structure to discuss the effectiveness and robustness of the developed Online-FLMVOC. Finally, Section 3 summarizes the results and discussions drawn from the previous sections and introduces the reader to the conclusion chapter.

4.1 Fuzzy Logic Multi Verse Optimal Control System (FLMVO)

4.1.1 Earthquake Excited Structure

The real-time response has been obtained to assess the performance of the developed semi-active vibration control system. The maximum response has been compared with the well-known Clipped-Optimal (CO) and Modified Bang-Bang (MBB) semi-active vibration control strategies [74], as well as the Passive-On control case. Table 4.1 shows the base rules weights for the selected optimal fuzzy logic controller. As it can be seen, the high weight value (70-98) % has primarily been assigned to the maximum voltage membership function (MV). Meanwhile, the low voltage membership function (LV) has been assigned with a low weight percentage in the range of (0-30) %; this indicates the reliability of the formulated fuzzy logic controller and the optimization methodology.

Table 4.1: Base rules weights for the optimal fuzzy logic controller (earthquake excited structure)

<i>Drift</i>	<i>Acceleration</i>						
	<i>LN</i>	<i>N</i>	<i>SN</i>	<i>Z</i>	<i>SP</i>	<i>P</i>	<i>LP</i>
<i>LN</i>	MV 0.9373	MV 0.1615	HV 0.0087	MV 0.9589	MeV 0.9810	MeV 0.9810	LV 0.6237
<i>N</i>	MV 0.5152	HV 0.0027	NV 0.7539	NV 0.5092	MeV 1	MeV 0.8117	LV 0.5220
<i>SN</i>	NV 0.8128	NV 0.4435	NV 0.1685	MeV 0.1978	LV 0.6322	LV 0.0038	LV 0.7555
<i>Z</i>	MeV 0.6962	MeV 0.6840	LV 0.0870	LV 0	LV 0	LV 0.9426	LV 0.0208
<i>SP</i>	NV 0.2151	MeV 0.3215	LV 0.3353	LV 0.4588	MeV 0.7936	NV 0.3565	NV 0.3510
<i>P</i>	MeV 0.5647	NV 0.0495	NV 0.7531	NV 0.7411	HV 0.4303	HV 0.0666	MV 0
<i>LP</i>	NV 0.8835	NV 0.8650	HV 0.1518	HV 0.4065	HV 0.6866	MV 0.1245	MV 0.6994

The comparison results are shown in Table 4.2. The results indicated that a competitive performance of the developed FLMVOC system in mitigating the story drift and absolute acceleration along all structure stories. FLMVOC demonstrated an average reduction of 44% in top story drift and absolute acceleration when subjected to diverse earthquake amplitudes. As indicated in Figures 4.1- 4.2 the maximum reductions in top story drift and absolute acceleration were similar for both CO and MBB strategies, equal to 44% and 48%, respectively under the effect of the El Centro earthquake. However, FLMVOC showed superiority over other control strategies when the structure was excited by the near-field high-magnitude Northridge earthquake. FLMVOC is superior in terms of robustness and adaptivity compared to reference control strategies as it utilizes a single controller that can withstand uncertainties in excitation and provide rational response control action. Unlike reference control strategies, FLMVOC doesn't require parameter changes to adapt to uncertainties, making it more adaptive and efficient.

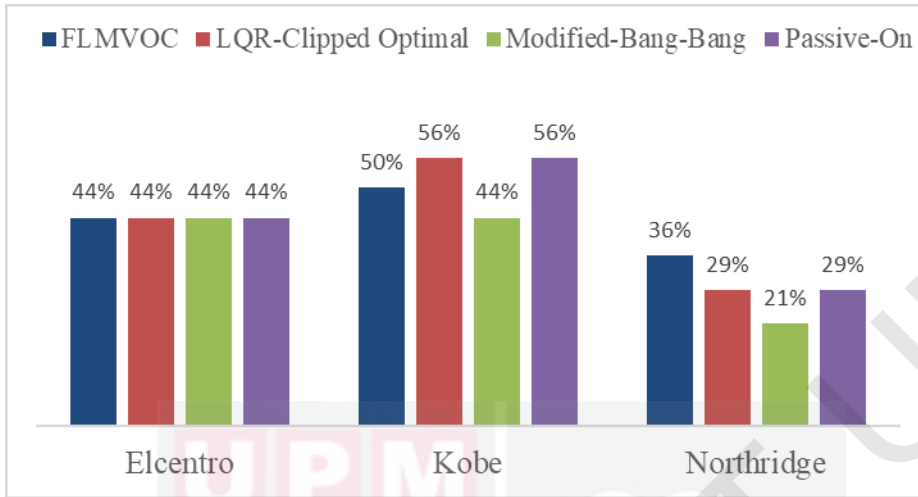


Figure 4.1: Third floor drift reduction by the considered control strategies

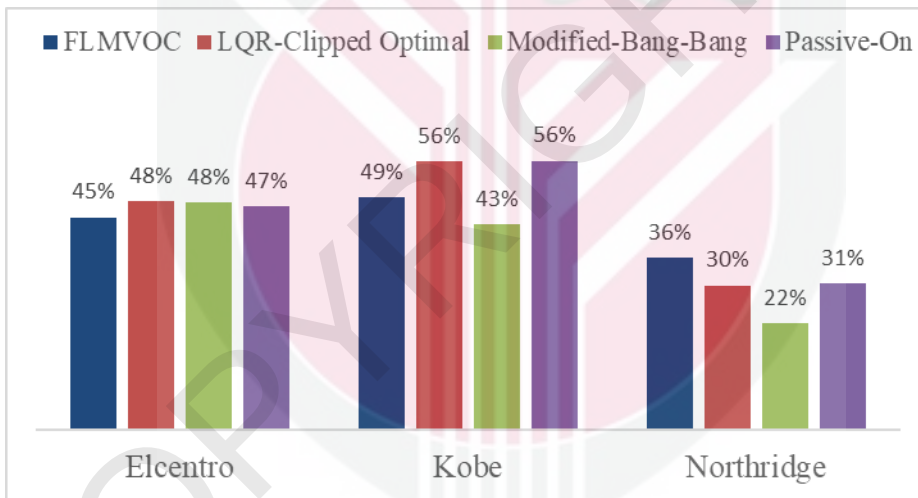


Figure 4.2: Third floor acceleration reduction by the considered control strategies

Furthermore, FLMVOC strategy demonstrated significant power-saving capabilities and effectively utilized control force compared to the CO and MBB strategies. Figure 4.3(a-c) present the real-time third-floor response and the produced MR control force under the effect of the El Centro earthquake, demonstrating the competitive performance of FLMVOC compared to other control strategies. Moreover, a control force index has been employed for an easy comparison and evaluation of the developed FLMVOC in comparison with other considered control strategies. FLMVOC has a control index of 0.529, compared to 0.875 and 0.873 for CO and MBB, respectively which depicts its superiority to achieve efficient control action by using only 52-67% of the control force produced by the reference control strategies. Table 4.2 presents the

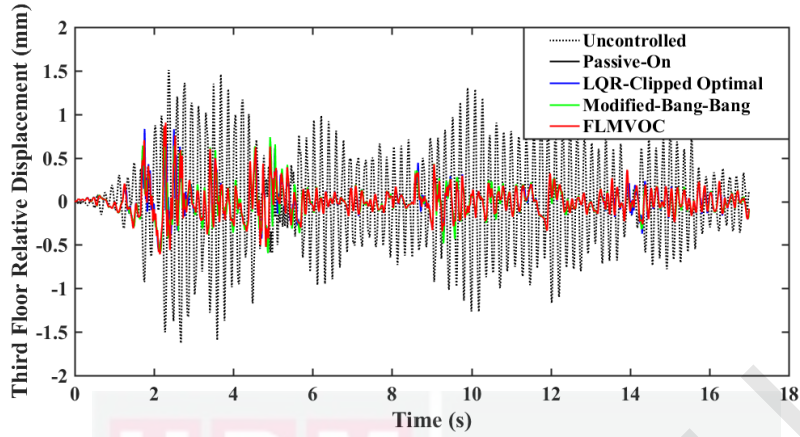
response of the FLMVOC system in comparison to the considered CO, MBB, and Passive On control strategies.

Figure 4.4 shows the maximum structural response to the considered earthquakes. The maximum relative story displacement for the uncontrolled structure is about 6 mm under the effect of El Centro earthquake and 10 mm under both the Kobe and Northridge earthquakes. Despite the high disparities in the intensity between far-field and near-field earthquakes (about 200%), the developed control system has effectively mitigated the structural response for all considered load cases.

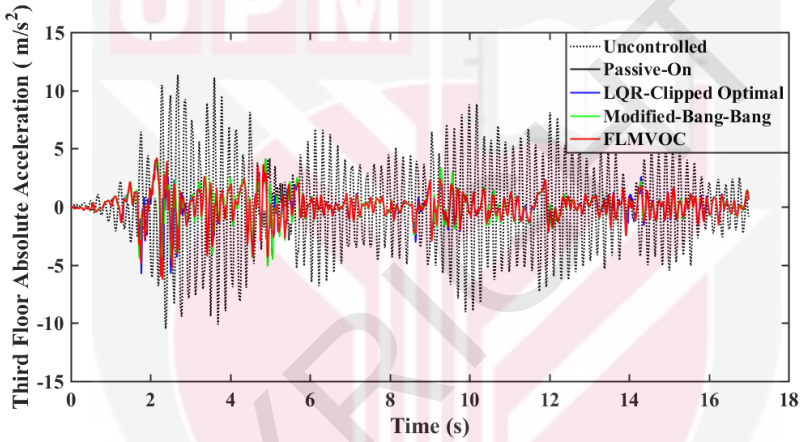
The first story real-time response (Figures 4.5-4.6) proves the outstanding performance of the control system to diminish the structural response in real-time include of both floors' drift and acceleration when the seismic excitation is applied to the structure.

It can be seen from Table 4.2 that the reduction in story drift at the first floor for the structure utilized with the developed FLMVOC control system excited by El Centro, Kobe, and Northridge earthquakes are 60%, 53%, and 41%, respectively. In contrast, the average drift reduction for the three floors is 50%, 51%, and 37% under the effect of El Centro, Kobe, and Northridge earthquakes, respectively.

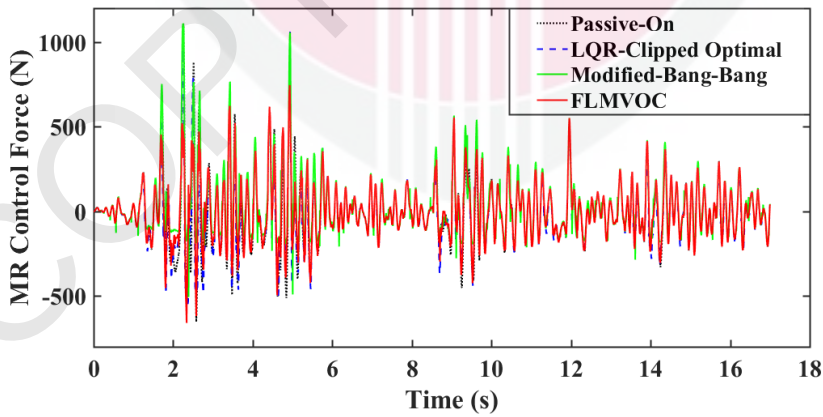
As indicated in Table 4.2, the reduction in story drift for the second and third floors is 45% and 44%, respectively. At the same time, the reduction in absolute acceleration is 31% and 45% for the mentioned floors, under the effect of El Centro earthquake. The same structural behaviour has been observed for other applied earthquakes. Albeit the contradictory relationship between the story drift and story acceleration as reducing one can violate the other [90], the developed FLMVOC is successfully overcome this response interaction by adequate formulation of fuzzy logic base rules which minimizing the story acceleration as much possible without violating the story drift. Despite of deploying MR damper in the only first floor, the control system effectively mitigated the response of all other floors by dissipating the applied ground motion energy in the first floor. Considering the absolute acceleration response, FLMVOC control system has successfully reduced the structural acceleration at the controlled (first) floor by 38%, 17%, and 10% under the effect of El Centro, Kobe, and Northridge earthquakes, respectively. However, it can be indicated that the reduction in acceleration is inversely proportional to the earthquake intensity.



a) Third Floor Relative Displacement



b) Third Floor Absolute Acceleration



c) Real Time Control Force

Figure 4.3: Comparison of real time structural system response for the considered control strategy (el centro earthquake)

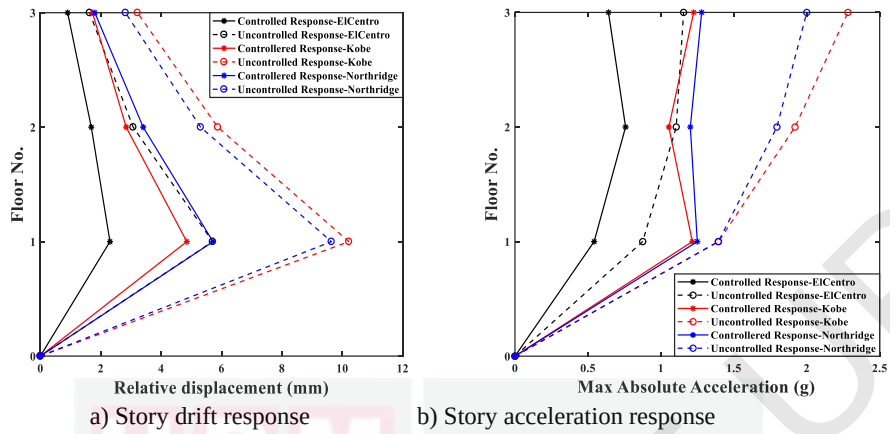
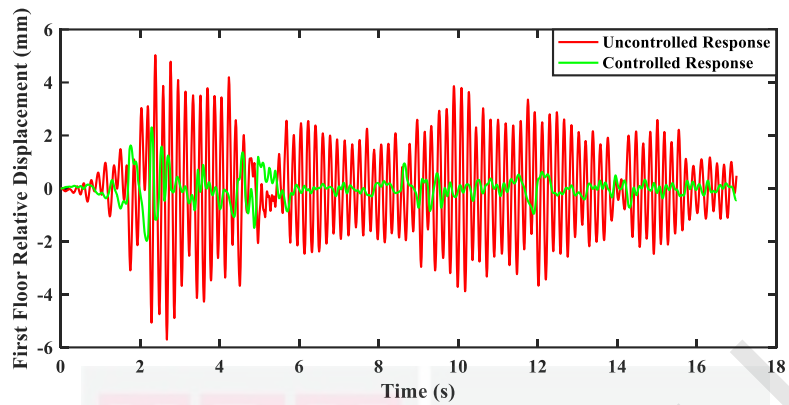


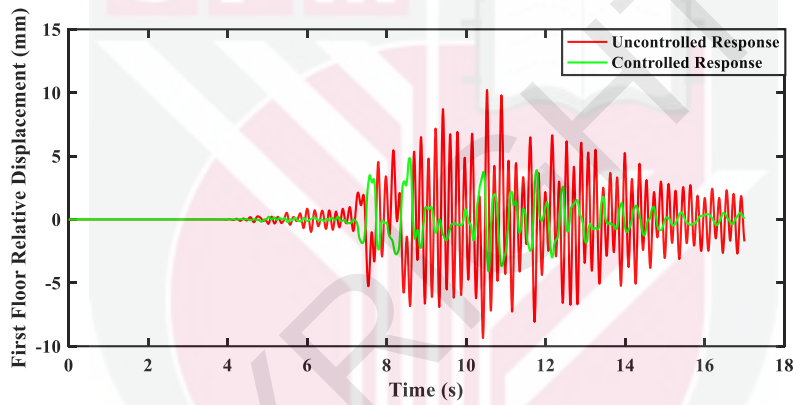
Figure 4.4: Maximum controlled and uncontrolled response for the structure subjected to different earthquakes

Table 4.2: Maximum floors' response compared with reference control strategies

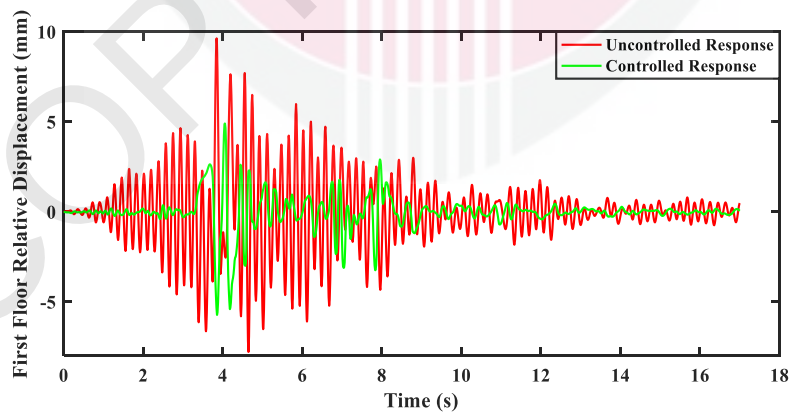
Earthquake	El Centro 1940			Kobe			Northrid	
	Story Drift (m)	Story Acce.(m/s ²)	Control Force(N)	Story Drift (m)	Story Acce.(m/s ²)	Control Force(N)	Story Drift (m)	Story Acce.(m/s ²)
Un-Controlled	0.0057	8.5911	-	0.0102	13.6876	-	0.0096	13.6775
	0.0031	10.8437		0.0059	18.8327		0.0053	17.6166
	0.0016	11.3414		0.0032	22.3903		0.0028	19.6229
FLMVOC	0.0023	5.3258	745.6	0.0048	11.3536	714.8	0.0057	12.2616
	0.0017	7.4394		0.0029	10.3119		0.0034	11.7932
	0.0009	6.2903		0.0016	11.4630		0.0018	12.5549
Modified quasi-Bang-Bang	0.0020	8.0011	1106.4	0.0051	10.5162	1155	0.0063	13.7783
	0.0014	5.7418		0.0027	10.9882		0.0038	13.5732
	0.0009	5.9307		0.0018	12.7384		0.0022	15.2410
Clipped Optimal	0.0020	5.2837	1108	0.0043	10.8889	1109	0.0056	11.6457
	0.0015	5.2530		0.0026	9.5254		0.0032	13.0171
	0.0009	5.9027		0.0014	9.7713		0.0020	13.6943
Passive On	0.0017	3.5098	1108	0.0043	8.5484	1175	0.0044	9.7169
	0.0015	4.9965		0.0027	9.3485		0.0034	12.4595
	0.0009	6.0227		0.0014	9.7586		0.0020	13.6095



a) Displacement Response (El Centro)

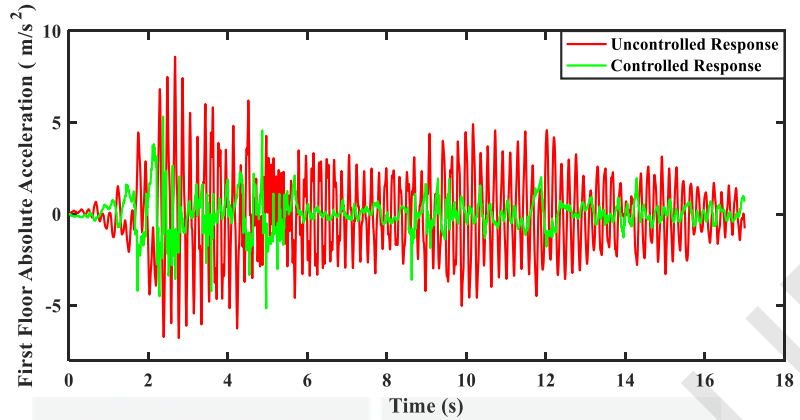


b) Displacement Response (Kobe)

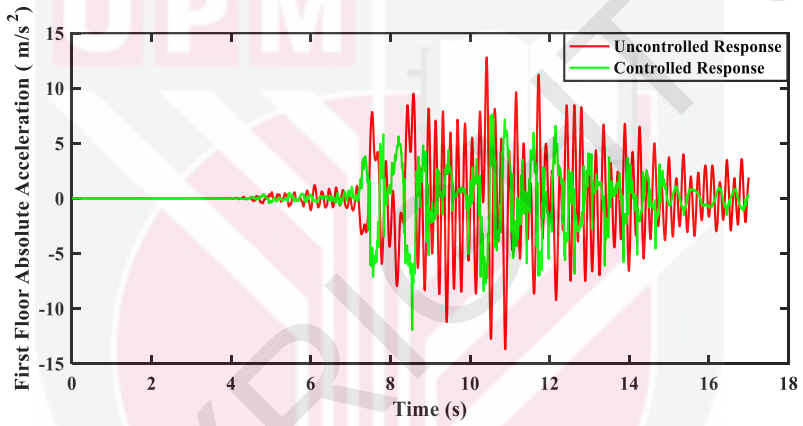


c) Displacement Response (Northridge)

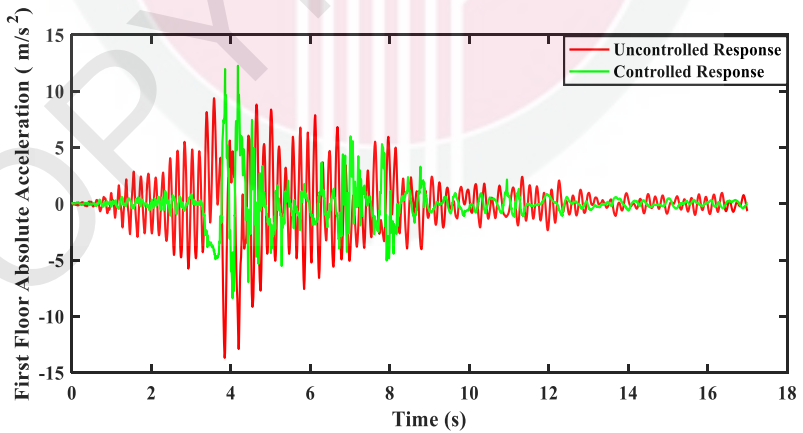
Figure 4.5: Realtime displacement response for the structure with optimal FL



a) Acceleration Response (El Centro)

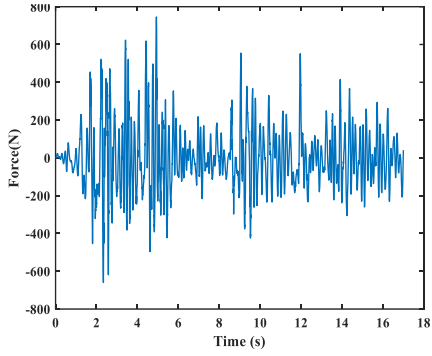


b) Acceleration Response (Kobe)

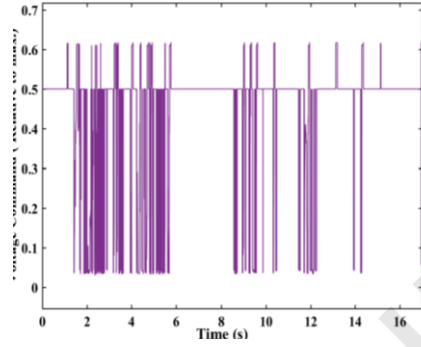


c) Acceleration Response (Northridge)

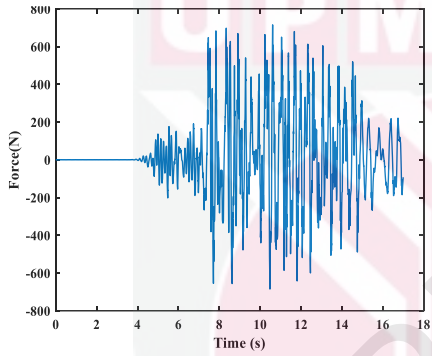
Figure 4.6: Realtime acceleration response for the structure with optimal FLC (FLMVOC Control Algorithm)



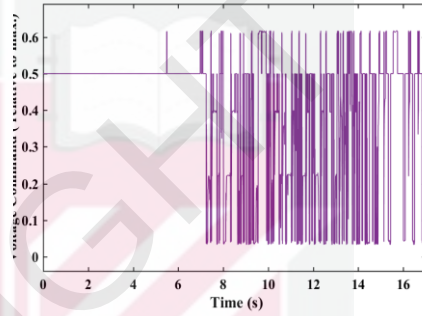
a) Real-time MR Control Force (El Centro)



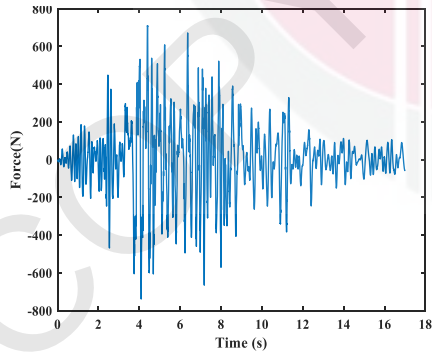
d) Real-time MR Voltage (El Centro)



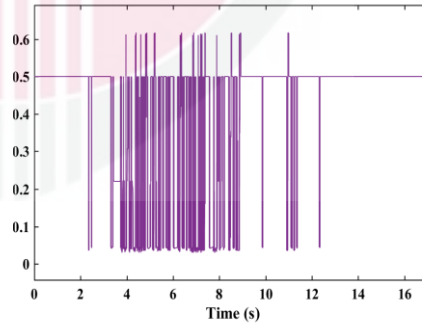
b) Real-time MR Control Force (Kobe)



e) Real-time MR Voltage (Kobe)



c) Real-time MR Control Force (Northridge)



f) Real-time MR Voltage (Northridge)

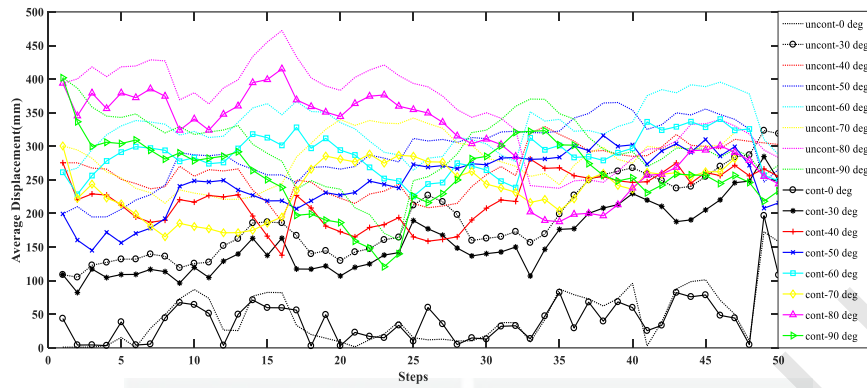
Figure 4.7: Real-time MR control force and commanding voltage under different earthquakes

4.1.2 Wind Excited Structure

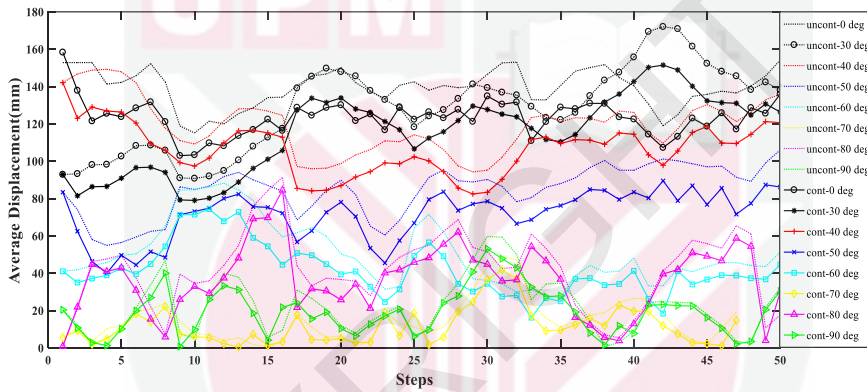
The optimal fuzzy logic controller from section 3.2.7.3 is deployed in the high-rise building stated in section 3.2.7.1. For the sake of efficient control performance in each response component (i.e., along wind, across wind and rotational), and owing to the discrepancy between across wind and along wind structural response, the concept of decentralized system was applied by implementing one controller for each MR damper at the selected eight control points (four in X-Direction and four in Y-Direction).

The real-time response due to the three load components with multiple load directions (wind attack angle (θ) = $0^\circ, 30^\circ, 40^\circ, 50^\circ, 60^\circ, 70^\circ, 80^\circ, 90^\circ$) is compared with the corresponding uncontrolled response. Figure 4.8(a-c) and Figure 4.9(a-c) show the real-time average response of four points in each direction, while the rotational response is related to the average of all control points. Since the structure's occupant category is office building [80], a threshold of 20 milli-g for the floor's acceleration response is utilized [91] in mapping the acceleration membership functions of the FLC. In the same way, the values of maximum uncontrolled story drift and maximum voltage capacity for the MR damper's current driver are used in mapping the membership functions for the drift and commanding voltage, respectively. The feature of defining input and output membership function relative to design values enables us to implement the controller in any structural system. Furthermore, it offers a tuning tool without the need to run optimization processing since the system performs sufficiently.

It can be seen in Figures 4.8 and 4.9 that the controller is effectively able to control the response at each time step, keeping it within the permissible limits (10 mm for story drift and 0.2-0.25 m/s² for acceleration) in both along wind and across wind directions.



a) Displacement Response in Y-Direction



b) Displacement Response in X-direction

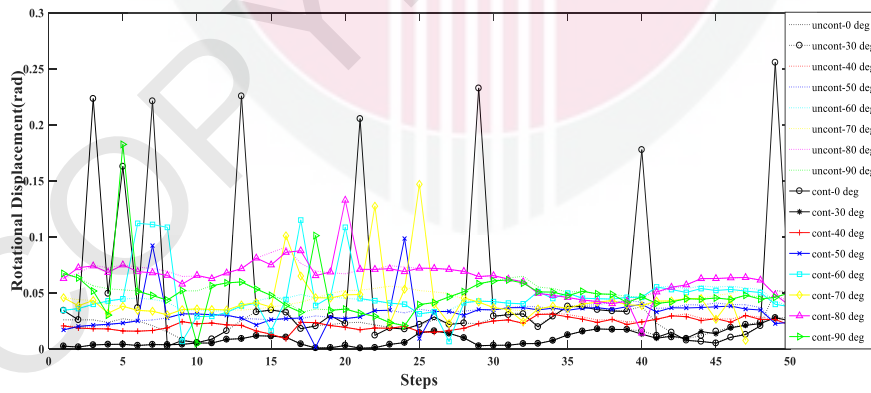
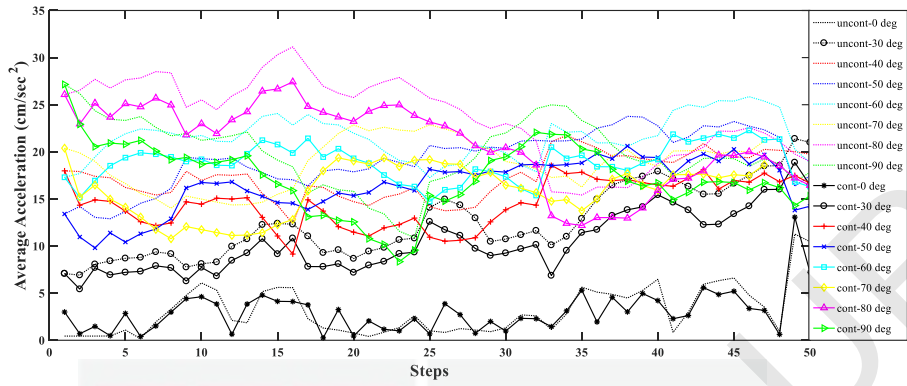
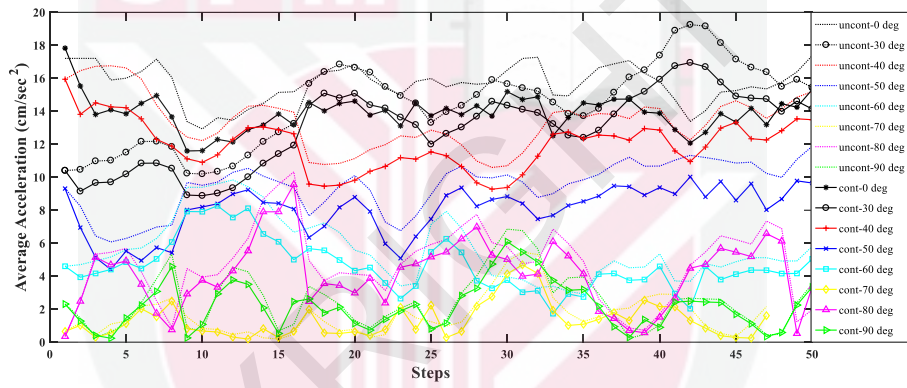


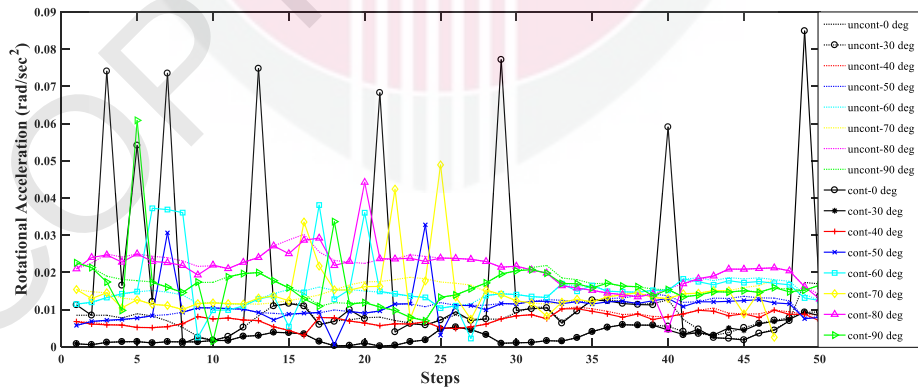
Figure 4.8: Uncontrolled and controlled displacement response under multidirectional wind load



a) Acceleration Response in Y-Direction



b) Acceleration Response in X-Direction



c) Rotational Acceleration Response

Figure 4.9: Uncontrolled and controlled acceleration response under multidirectional wind load

Since the Torsional vibrations are a consequence of the twisting force along the vertical axis of the building. This force arises from the uneven distribution of wind load [23], a common occurrence in controlled structures [19] where the developed vibration control system independently manages lateral displacement in each direction.

Further, the rotational velocity has been identified as a comfort criterion for structures affected by wind load in recent publication of Applied Technology Council (ATC)[91]. Therefore, this study discusses the rotational response to ensure the reliability of the developed vibration control system in addressing the specified problems and achieving the set objectives. Although the rotational response is found over the uncontrolled response when pure along wind load case happens, it was minimal in value and had not exceeded the thresholds specified in ATC Design Guide 3[91].

Table 4.3 shows the building's maximum response considering different load directions. The percentages of reduction in floors' displacement along the Y-axis are 12.0%, 14.7%, 13.5%, 13.9%, 15.7%, 12.1%, and 16.3% under the effect of wind attack angles of respectively. Similarly, the reduction in acceleration response along Y-axis had been 11.8%, 14.6%, 13.3%, 13.8%, 15.4%, 11.9%, and 15.6%, respectively.

For the (0°) wind attack angle, a leap in both displacement and acceleration response in Y-direction can be observed at several time steps; however, its values are relatively small and do not exceed the allowable limits. Figure 4.10(a-f) compares the controlled and uncontrolled maximum displacement and acceleration response.

The destabilization state of the structural control system deployed with semi-active dampers would not happen in a real application; hence, there is more than one reason that can interpret the system behavior under the effect of the (0°) component of wind load. First, the difference in building dimension results in a strong effect of vortex shedding along the Y-axis. The second reason is related to the optimization criteria, which depended on one attack angle of wind load (90°) during the optimization phase. The third is that the objective functions had been formulated to evaluate the response along the Y-direction only where the worst-case expected to happen under the effect of the (90°) component of wind load. The control force tracing approach is another factor that affects the simulation results where the force was applied to the structure in active force scheme.

Considering the response in X-direction, a reduction of 9.9%, 12%, 4.8%, 11.6%, 15.8%, 14.1%, 7.4%, and 11.3% of the uncontrolled displacement is obtained for wind attack angles of 0° , 30° , 40° , 50° , 60° , 70° , 80° , and 90° respectively.

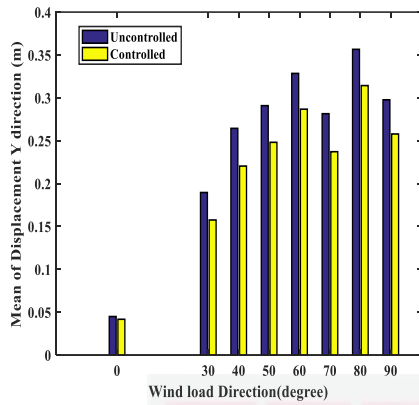
Table 4.3: Maximum building's response under the effect of multi directional wind load

<i>Response Type*</i>		<i>Wind Load Attack Angle</i>							
		0°	30°	40°	50°	60°	70°	80°	90°
Drift-X	Controlled	1.900E-03	1.768E-03	1.685E-03	1.060E-03	8.507E-04	5.074E-04	1.022E-03	6.946E-04
	Uncontrolled	1.860E-03	2.017E-03	1.785E-03	1.249E-03	1.023E-03	5.878E-04	1.102E-03	7.737E-04
Drift-Y	Controlled	2.473E-03	3.586E-03	3.530E-03	3.935E-03	4.249E-03	3.699E-03	5.219E-03	4.326E-03
	Uncontrolled	2.154E-03	4.067E-03	4.134E-03	4.536E-03	1.632E-03	4.337E-03	5.928E-03	5.135E-03
Displacement-X	Controlled	1.379E-01	1.515E-01	1.421E-01	8.950E-02	7.433E-02	4.177E-02	8.451E-02	5.300E-02
	Uncontrolled	1.530E-01	1.720E-01	1.492E-01	1.012E-01	8.825E-02	4.862E-02	9.126E-02	5.975E-02
Displacement-Y	Controlled	1.967E-01	2.847E-01	2.810E-01	3.160E-01	3.405E-01	2.883E-01	4.151E-01	3.365E-01
	Uncontrolled	1.726E-01	3.234E-01	3.293E-01	3.652E-01	3.955E-01	3.420E-01	4.722E-01	4.020E-01
Rotational Displacement	Controlled	2.557E-04	2.790E-05	3.094E-05	9.855E-05	1.150E-04	1.470E-04	1.327E-04	1.826E-04
	Uncontrolled	5.204E-05	2.778E-05	3.219E-05	4.306E-05	5.624E-05	5.598E-05	9.079E-05	6.731E-05
Acceleration-X	Controlled	1.585E-01	1.701E-01	1.460E-01	1.021E-01	8.417E-02	4.866E-02	9.911E-02	6.339E-02
	Uncontrolled	1.758E-01	1.931E-01	1.685E-01	1.200E-01	1.009E-01	5.627E-02	1.070E-01	7.101E-02
Acceleration-Y	Controlled	1.397E-01	1.893E-01	1.863E-01	2.069E-01	2.238E-01	2.048E-01	2.759E-01	2.729E-01
	Uncontrolled	1.138E-01	2.143E-01	2.180E-01	2.385E-01	2.596E-01	2.298E-01	3.132E-01	3.054E-01
Rotational Acceleration	Controlled	8.490E-04	9.326E-05	1.024E-04	3.279E-04	3.810E-04	4.889E-04	4.421E-04	6.085E-04
	Uncontrolled	1.728E-04	9.331E-05	1.068E-04	1.420E-04	1.858E-04	1.868E-04	3.020E-04	2.259E-04
Rotational Velocity**	Controlled	3.039E-01	3.313E-02	3.676E-02	1.171E-01	1.367E-01	1.747E-01	1.578E-01	2.170E+00
	Uncontrolled	6.188E-02	3.321E-02	3.825E-02	5.112E-02	6.796E-02	6.657E-02	1.079E-01	8.007E-02

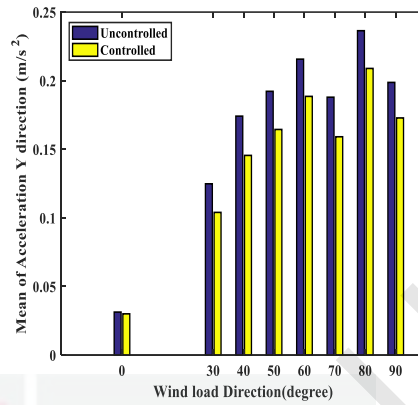
Notes:

* Drift's values are unit less, acceleration values are in (m/s²), rotational acceleration is in (rad/s²), rotational velocity is in (milli-rad/s).

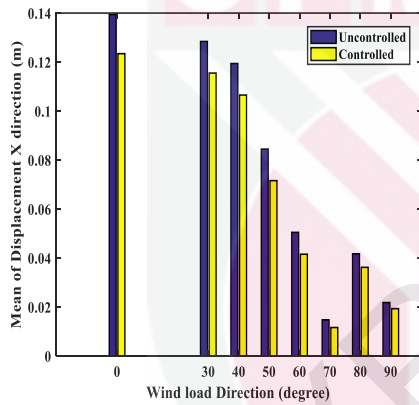
** Permissible Acceleration = 20 milli-g (0.2 m/s²), Permissible Rotational Velocity = 5 milli-rad/s[91].



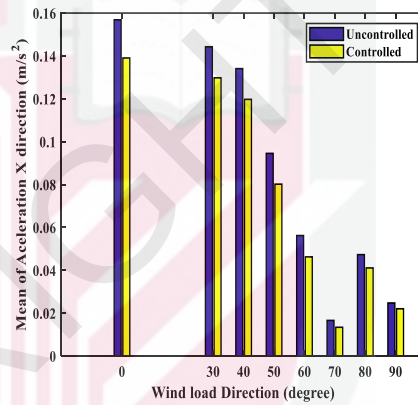
a) Maximum Displacement (Y-direction)



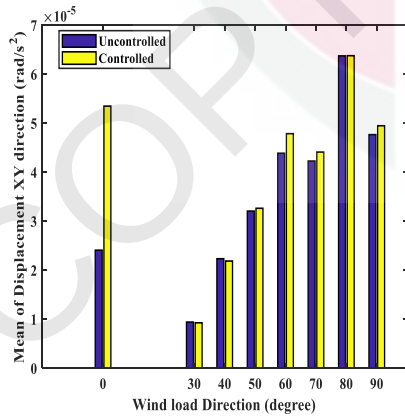
b) Maximum Acceleration (Y-direction)



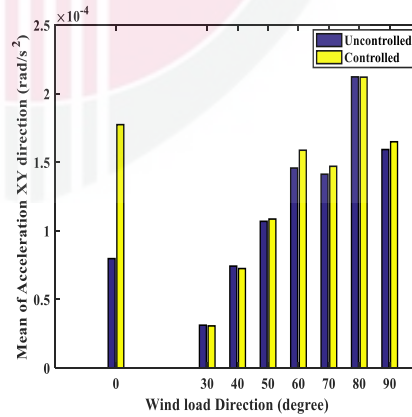
c) Maximum Displacement (X-direction)



d) Maximum Acceleration (X-Direction)



e) Rotational displacement



f) Rotational Acceleration

Figure 4.10: A comparison between controlled and uncontrolled maximum response values

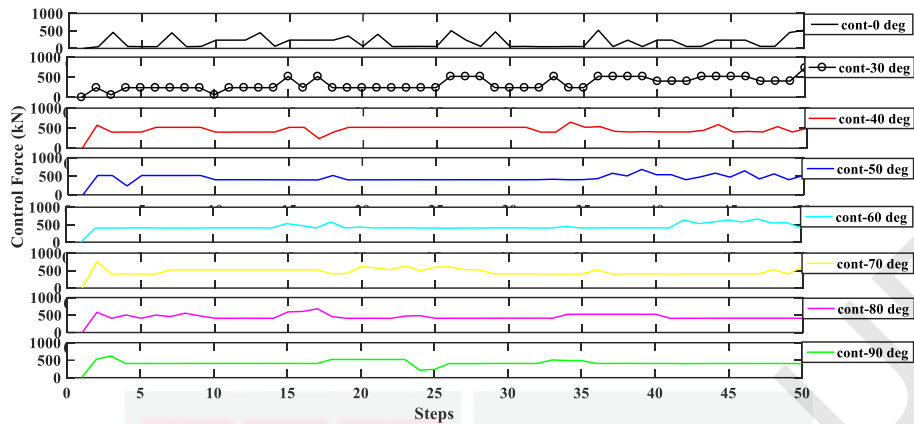
The reduction percentages in acceleration response are 10.1%, 12%, 4.9%, 11.5%, 15.9%, 14.0%, 7.4%, and 11.1% of the uncontrolled acceleration under wind load attack angles of 0° , 30° , 40° , 50° , 60° , 70° , 80° and 90° , respectively. The reduction in the acceleration response is approximately similar to the achieved reduction in the displacement response under the considered load criteria.

Utilizing active force scheme means that although the FLC can implicitly overcome the probability of the destabilization state of the active force scheme, the action of passive-off control force cannot be avoided, which may cause an increase in the response under relatively small excitation forces. Figure 4.11 shows the real-time control force under different wind load attack angles.

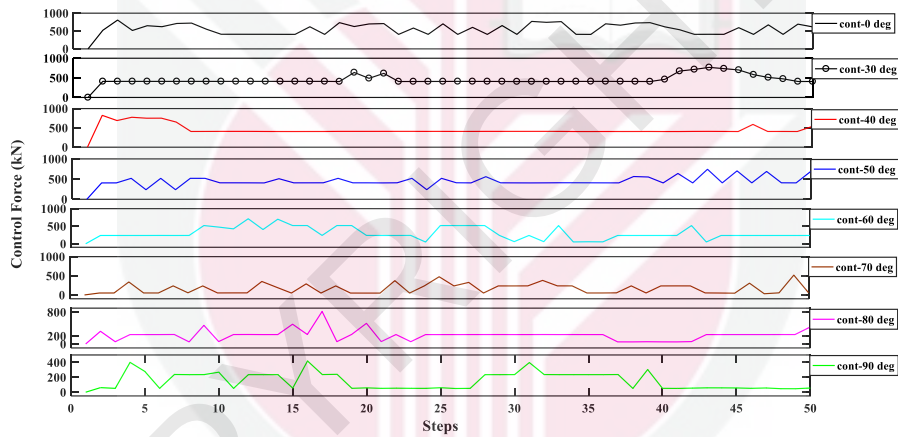
As one of the comfort criteria utilized recently in ATC Guide 3 to assess the design of wind excited structures, rotational velocity is also not exceeded the specified threshold (5 milli-rad/s), Table 4.3.

A deduction can be drawn from the above discussion that the developed FLMVOC algorithm is capable not only of controlling the response of the structure for both displacement and acceleration, but it is also capable of adaptively withstanding the interacted action of simultaneously applied excitation on full degree of freedom structure, which stands as one of the research problems.

Moreover, applying a decentralized control system concept enables FLMVOC to adaptively manage the control system's resources even if the optimum number and capacity of the MR dampers are not obtained. This performance can be seen when relatively small values of external forces are exerted on one building side rather than the other; for example, small control forces along X-axis (across wind) have been generated by the vibration control system under the effect of (90°) wind attack angle. Meanwhile, the structural response along Y-axis (along wind) has been controlled by maximum influential control forces.



a) Real-time Control Force Along Y direction



b) Real-time Control Force Along X-direction

Figure 4.11: Real-time commanded control force by FLMVOC control system

4.2 Online Fuzzy Logic Multi Verse Optimal Control System (Online-FLMVOC)

4.2.1 Earthquake Excited Structure

The developed Online-FLMVOC vibration control system has been implemented in the benchmark three story shear wall structure subjected to real earthquakes, (sections 3.3.5.1- 3.3.5.4). Three control strategies were employed for performance evaluation; FLMVOC, Modified quasi Bang-Bang (MBB) and LQR-Clipped Optimal (CO).

Figure 4.12 shows the initial (feed-in) data for the FIS Memory. In this study phase, random fuzzy logic controllers, including those produced from a wind-excited structural system, were fed to initiate the FIS memory.

Figures 4.13 and 4.14 represent the obtained optimum fuzzy logic controllers (FLCs) in the FIS memory after completing the simulation for sixteen seconds of external excitation. Although the fed-in controllers have been different in base rules and membership position values, the convergence of the solutions indicates the excellent performance of the developed Online-FLMVOC algorithm.

Table 4.4 and Table 4.5 show the complete parameters for the FL controllers in the FIS memory under the effect of El Centro and Northridge earthquakes, respectively. As can be noted, The FLCs are well organized in the memory according to the desired priority. The first slot of the memory is always filled with the best obtained FLC of minimum fitness functions (i.e. minimum story drift and story acceleration). Meanwhile, the last memory slot (Slot 10) is filled with FLCs of higher values of objective functions, which depicts the intelligent action of the developed sorting and updating technique.

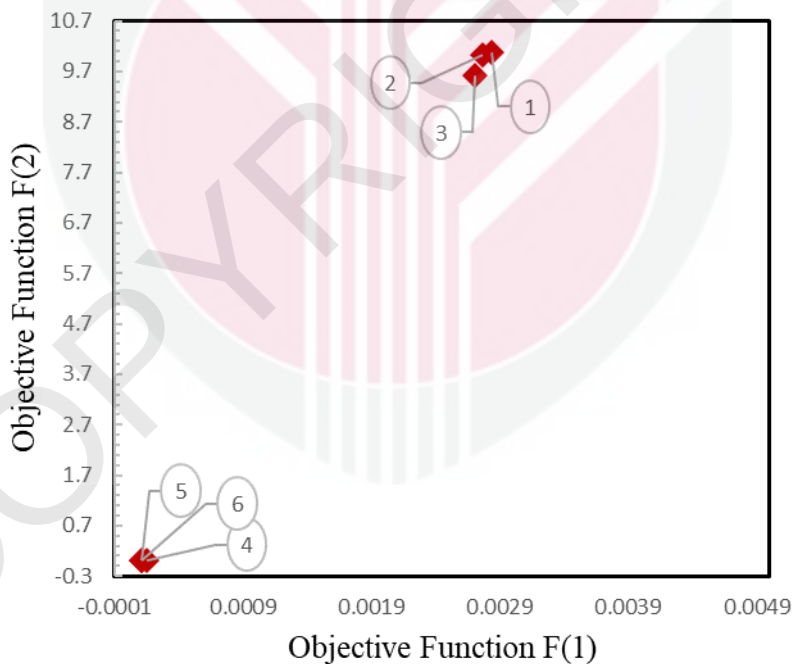


Figure 4.12: Initial FLCs in the FIS memory

Despite the equality in the value of the first objective function($F(1)$) for sequent FLCs, the system is continuously searching for the best solution by comparing the second objective function without discarding the controllers producing minimum story drift (minimum $F(1)$). This performance can be noted in tables 4.4 and 4.5 when sequent FLCs in the FIS memory are of approximately equal value (1×10^{-3}) for $F(1)$ but with different values of $F(2)$ sorted ascendingly for both El Centro and Northridge seismic load.

Despite the disparity in the $F(2)$ values (in the range of 9.6 to 10.1) for the FLCs (5,6,7) and (6,7,8) (Figures 4.13 and 4.14, Tables 4.4 and 4.5, respectively) compared with other FLCs in the FIS memory, they have been kept in the FIS memory with different priority since other FLCs do not dominate its $F(1)$ values.

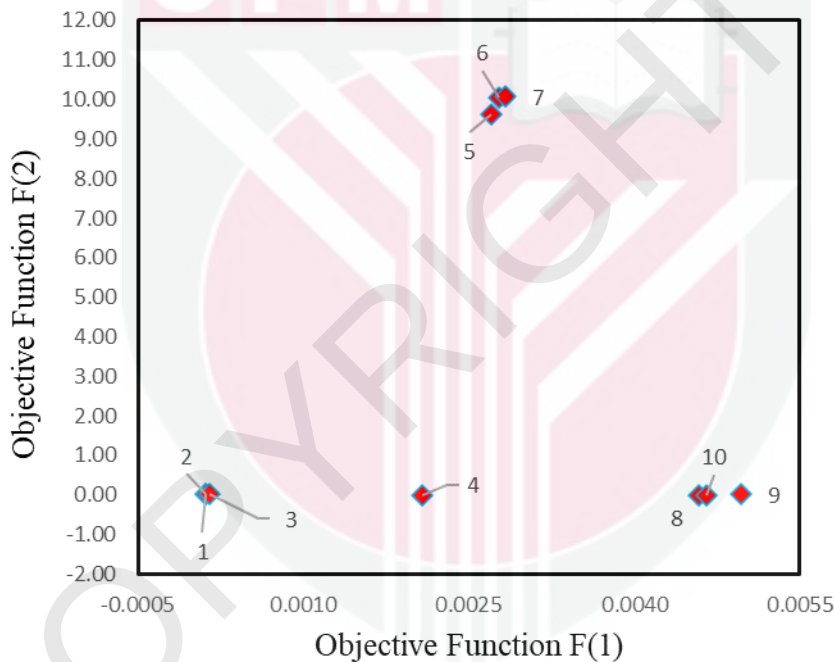


Figure 4.13: Obtained optimum FLCs in the FIS memory (El Centro Earthquake)

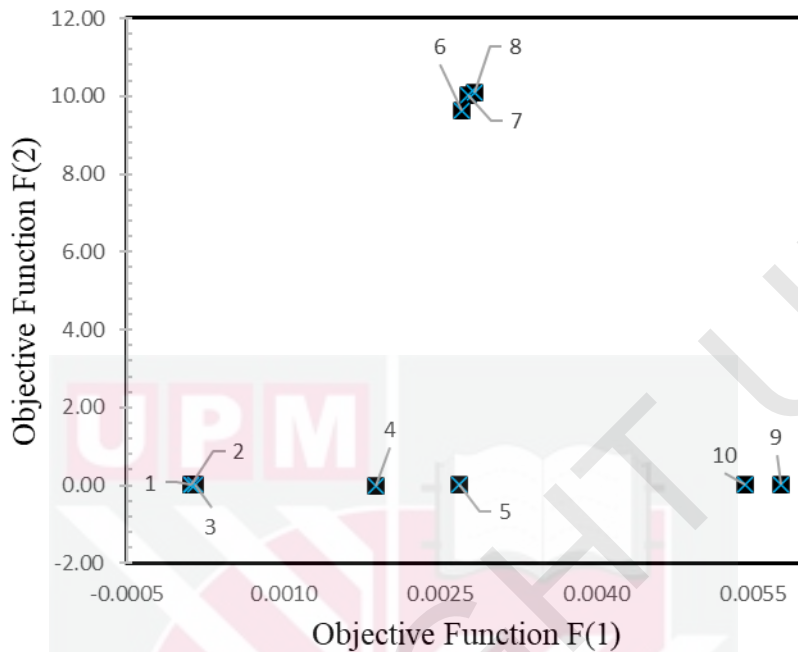


Figure 4.14: Obtained optimum FLCs in the FIS memory (Northridge Earthquake)

Online-FLMVOC has prioritised controlling the story drift response, which was the desired performance through the structural system life. A forementioned action proves the intelligent response of the developed Online-FLMVOC system to determine the desired control action in real-time and then manage the updating and selection techniques of FIS memory accordingly.

Table 4.6 and Table 4.7 show the determined base rules weights for each FLC according to its priority in the FIS memory. Although most FLCs in the FIS memory produce rationally equal values of objective functions, the rule weights differ since each controller was produced during different time series. It should be noted that most of the rules are assigned with a range of (30-100 %) of weights which proves the reliability of the formulated fuzzy logic system and the developed optimization algorithm.

Table 4.4: The obtained optimum FLCs in the FIS memory (El Centro Earthquake)

Controller		Position Data for the Membership Functions																				Objective Functions	
		Input (1): Story Drift										Input (2): Story Absolute Acceleration											
		LN	N	SN	Z	SP	P	LP	LN	N	SN	Z	SP	P	LP	LV	MeV	NV	HV	MV			
1	a	NC*	-0.6466	-0.3934	-0.1749	0.0671	0.3190	0.7800	NC	-0.6010	-0.5000	-0.1602	0.0146	0.3199	0.7624	NC	0.1130	0.2500	0.5420	0.6735			
	b	NC	-0.5500	-0.3000	-0.1500	0.1304	0.4018	0.8500	NC	-0.5000	-0.2560	-0.1000	0.1037	0.3588	0.9000	NC	NC	NC	NC	NC			
	c	-0.8289	-0.3780	-0.1000	0.1107	0.2357	0.6473	0.9000	-0.9000	-0.3729	-0.1072	0.0809	0.2165	0.7412	0.9000	0.0875	0.3232	0.5095	0.6250	0.9342			
	d	-0.8000	-0.3001	-0.0477	0.2000	0.3096	0.9000	0.9500	-0.7000	-0.3295	-0.0533	0.2000	0.2500	0.8450	0.9730	Null**	Null	Null	Null	Null			
2	a	NC	-0.7209	-0.4231	-0.1327	0.0926	0.2800	0.7506	NC	-0.7752	-0.3218	-0.2000	0.0060	0.3299	0.7709	NC	0.0865	0.3157	0.5096	0.6717			
	b	NC	-0.5500	-0.2613	-0.1112	0.1182	0.3500	0.9000	NC	-0.5500	-0.2000	-0.1000	0.1414	0.3500	0.8602	NC	NC	NC	NC	NC			
	c	-0.8664	-0.4075	-0.1415	0.0536	0.2456	0.6246	0.9500	-0.8529	-0.4500	-0.1016	0.0837	0.2484	0.7473	0.9500	0.0536	0.3295	0.5390	0.7500	0.9381			
	d	-0.7967	-0.3000	-0.0813	0.1710	0.4090	0.8000	1.0000	-0.7000	-0.3000	-0.0576	0.1372	0.3353	0.8148	1.0000	Null	Null	Null	Null	Null			
3	a	NC	-0.7813	-0.4802	-0.2000	0.0694	0.2807	0.8500	NC	-0.7294	-0.3000	-0.1613	0.0935	0.2800	0.8500	NC	0.1024	0.3394	0.5381	0.7375			
	b	NC	-0.5347	-0.2000	-0.1500	0.1354	0.3917	0.8500	NC	-0.5500	-0.2632	-0.1227	0.1014	0.3968	0.9000	NC	NC	NC	NC	NC			
	c	-0.9000	-0.4500	-0.1132	0.0500	0.2474	0.7500	0.9412	-0.8329	-0.4031	-0.1231	0.0741	0.2513	0.6000	0.9000	0.1250	0.3750	0.4177	0.7111	0.9410			
	d	-0.7000	-0.3500	-0.0199	0.2000	0.4619	0.8605	1.0000	-0.7000	-0.3000	-0.0859	0.1402	0.4881	0.8881	0.9673	Null	Null	Null	Null	Null			
4	a	NC	-0.6772	-0.3925	-0.1377	0.0057	0.2947	0.7389	NC	-0.6150	-0.3026	-0.1859	0.0707	0.3359	0.8244	NC	0.1170	0.2949	0.4677	0.7075			
	b	NC	-0.5420	-0.2662	-0.0917	0.1000	0.3710	0.8667	NC	-0.5179	-0.2877	-0.1463	0.1334	0.4487	0.8568	NC	NC	NC	NC	NC			
	c	-0.8230	-0.3825	-0.1421	0.0965	0.2205	0.6644	0.9318	-0.8070	-0.3624	-0.1026	0.0629	0.2385	0.6030	0.9158	0.1104	0.2669	0.4727	0.7474	0.8968			
	d	-0.7255	-0.3156	-0.0971	0.1987	0.4434	0.8974	0.9808	-0.7368	-0.3135	-0.0588	0.1573	0.3945	0.8487	0.9882	Null	Null	Null	Null	Null			
5	a	NC	-0.7878	-0.4146	-0.1931	0.0891	0.3094	0.8097	NC	-0.7125	-0.4820	-0.1158	0.1000	0.3100	0.7306	NC	0.1218	0.2539	0.4870	0.7252			
	b	NC	-0.5191	-0.2000	-0.1452	0.1115	0.4304	0.8500	NC	-0.5401	-0.2918	-0.1046	0.1000	0.3777	0.8678	NC	NC	NC	NC	NC			
	c	-0.8786	-0.3883	-0.1468	0.0500	0.2834	0.7248	0.9156	-0.8605	-0.3500	-0.1103	0.0558	0.3000	0.6229	0.9336	0.0992	0.3317	0.5322	0.7500	0.9546			
	d	-0.7000	-0.3373	-0.0651	0.1431	0.5000	0.8787	0.9847	-0.7256	-0.3306	-0.0985	0.1683	0.2500	0.8388	0.9858	Null	Null	Null	Null	Null			

Table 4.4: Continued

Controller		Position Data for the Membership Functions																Objective Functions		
		Input (1): Story Drift								Input (2): Story Absolute Acceleration										
		LN	N	SN	Z	SP	P	LP	LN	N	SN	Z	SP	P	LP	LV	MeV	NV	HV	MV
6	a	NC	-0.8000	-0.3382	-0.1761	0.0957	0.2856	0.7769	NC	-0.7343	-0.3000	-0.1274	0.0911	0.3416	0.8500	NC	0.1178	0.3567	0.4580	0.7001
	b	NC	-0.5500	-0.2177	-0.1484	0.1000	0.4049	0.8500	NC	-0.5060	-0.2337	-0.1079	0.1111	0.4033	0.8500	NC	NC	NC	NC	NC
	c	-0.9000	-0.3956	-0.1000	0.0972	0.2696	0.6776	0.9000	-0.8355	-0.3500	-0.1453	0.1163	0.2327	0.7177	0.9443	0.1200	0.3045	0.5259	0.7500	1.0000
	d	-0.7662	-0.3355	-0.0157	0.1981	0.4128	0.8418	0.9951	-0.8000	-0.3161	-0.0968	0.1970	0.3590	0.9000	0.9500	Null	Null	Null	Null	Null
7	a	NC	-0.7292	-0.4554	-0.1163	0.0108	0.3500	0.7823	NC	-0.8000	-0.3427	-0.1000	0.0074	0.3500	0.7778	NC	0.0830	0.2500	0.4580	0.6670
	b	NC	-0.5500	-0.3000	-0.1358	0.1121	0.4500	0.9000	NC	-0.5025	-0.2006	-0.1100	0.1111	0.4125	0.9000	NC	NC	NC	NC	NC
	c	-0.8026	-0.4500	-0.1500	0.0635	0.2000	0.6825	0.9000	-0.8231	-0.4080	-0.1361	0.1500	0.2357	0.6000	0.9000	0.0988	0.3338	0.5410	0.6250	0.8750
	d	-0.7740	-0.3000	-0.0635	0.2000	0.4013	0.9000	1.0000	-0.7000	-0.3000	-0.0199	0.1000	0.2500	0.8000	1.0000	Null	Null	Null	Null	Null
8	a	NC	-0.6198	-0.4230	-0.1817	0.0713	0.2905	0.8273	NC	-0.6652	-0.4206	-0.1317	0.0111	0.3156	0.7260	NC	0.0950	0.3326	0.5106	0.6948
	b	NC	-0.5339	-0.2913	-0.0348	0.1153	0.4231	0.8969	NC	-0.5378	-0.2379	-0.1456	0.1383	0.4416	0.8930	NC	NC	NC	NC	NC
	c	-0.8996	-0.4011	-0.1222	0.1496	0.2840	0.6483	0.9333	-0.8722	-0.3889	-0.1051	0.1200	0.2850	0.6582	0.9408	0.1243	0.2547	0.4446	0.7346	0.9421
	d	-0.7751	-0.3078	-0.0153	0.1870	0.3994	0.8747	0.9899	-0.7370	-0.3005	-0.0807	0.1426	0.3790	0.8155	0.9764	Null	Null	Null	Null	Null
9	a	NC	-0.6828	-0.3972	-0.1220	0.0849	0.2950	0.8119	NC	-0.7970	-0.4901	-0.1415	0.0617	0.3044	0.8132	NC	0.1231	0.2904	0.4741	0.7280
	b	NC	-0.5392	-0.2652	-0.0167	0.1481	0.4132	0.8603	NC	-0.5417	-0.2383	-0.1413	0.1477	0.4463	0.8705	NC	NC	NC	NC	NC
	c	-0.8339	-0.4317	-0.1071	0.0664	0.2944	0.7154	0.9021	-0.8097	-0.4351	-0.1293	0.0730	0.2014	0.7455	0.9137	0.0721	0.2767	0.4548	0.7466	0.9144
	d	-0.7872	-0.3056	-0.0037	0.1005	0.4268	0.8492	0.9523	-0.7948	-0.3257	-0.0625	0.1389	0.4059	0.8925	0.9550	Null	Null	Null	Null	Null
10	a	NC	-0.6604	-0.3789	-0.1498	0.0122	0.3014	0.7243	NC	-0.6548	-0.4828	-0.1432	0.0779	0.3046	0.7810	NC	0.0861	0.3065	0.4974	0.7407
	b	NC	-0.5230	-0.2927	-0.0901	0.1461	0.4275	0.8872	NC	-0.5221	-0.2558	-0.1226	0.1177	0.4155	0.8824	NC	NC	NC	NC	NC
	c	-0.8215	-0.4056	-0.1156	0.1354	0.2290	0.7388	0.9150	-0.8411	-0.3822	-0.1072	0.1439	0.2607	0.6906	0.9404	0.1157	0.2963	0.5338	0.7184	0.9740
	d	-0.7202	-0.3384	-0.0056	0.1079	0.3534	0.8724	0.9736	-0.7798	-0.3376	-0.0719	0.1469	0.4026	0.8435	0.9931	Null	Null	Null	Null	Null
* NC: Not calculated; the value is pre-defined.																				
** Null: Not specified parameter for the defined membership function.																				

* NC: Not calculated; the value is pre-defined.

** Null: Not specified parameter for the defined membership function.

Table 4.5: The obtained optimum FLCs in the FIS memory (Northridge Earthquake)

Controller		Position (Figure 2)		Position Data for the Membership Functions																Objective Functions	
				Input (1): Story Drift								Input (2): Story Absolute Acceleration									
				LN	N	SN	Z	SP	P	LP	LN	N	SN	Z	SP	P	LP	LV	MeV		
1	a	NC*	-0.6466	-0.3934	-0.1749	0.0671	0.3190	0.7800	NC	-0.6010	-0.5000	-0.1602	0.0146	0.3199	0.7624	NC	0.1130	0.2500	0.5420	0.6735	0.0153
	b	NC	-0.5500	-0.3000	-0.1500	0.1304	0.4018	0.8500	NC	-0.5000	-0.2560	-0.1000	0.1037	0.3588	0.9000	NC	NC	NC	NC	NC	0.0001
	c	-0.8289	-0.3780	-0.1000	0.1107	0.2357	0.6473	0.9000	-0.9000	-0.3729	-0.1072	0.0809	0.2165	0.7412	0.9000	0.0875	0.3232	0.5095	0.6250	0.9342	
	d	-0.8000	-0.3001	-0.0477	0.2000	0.3096	0.9000	0.9500	-0.7000	-0.3295	-0.0533	0.2000	0.2500	0.8450	0.9730	Null**	Null	Null	Null	Null	
2	a	NC	-0.7209	-0.4231	-0.1327	0.0926	0.2800	0.7506	NC	-0.7752	-0.3218	-0.2000	0.0060	0.3299	0.7709	NC	0.0865	0.3157	0.5096	0.6717	0.0150
	b	NC	-0.5500	-0.2613	-0.1112	0.1182	0.3500	0.9000	NC	-0.5500	-0.2000	-0.1000	0.1414	0.3500	0.8602	NC	NC	NC	NC	NC	0.0001
	c	-0.8664	-0.4075	-0.1415	0.0536	0.2456	0.6246	0.9500	-0.8529	-0.4500	-0.1016	0.0837	0.2484	0.7473	0.9500	0.0536	0.3295	0.5390	0.7500	0.9381	
	d	-0.7967	-0.3000	-0.0813	0.1710	0.4090	0.8000	1.0000	-0.7000	-0.3000	-0.0576	0.1372	0.3353	0.8148	1.0000	Null	Null	Null	Null	Null	
3	a	NC	-0.7813	-0.4802	-0.2000	0.0694	0.2807	0.8500	NC	-0.7294	-0.3000	-0.1613	0.0935	0.2800	0.8500	NC	0.1024	0.3394	0.5381	0.7375	0.0155
	b	NC	-0.5347	-0.2000	-0.1500	0.1354	0.3917	0.8500	NC	-0.5500	-0.2632	-0.1227	0.1014	0.3968	0.9000	NC	NC	NC	NC	NC	0.0001
	c	-0.9000	-0.4500	-0.1132	0.0500	0.2474	0.7500	0.9412	-0.8329	-0.4031	-0.1231	0.0741	0.2513	0.6000	0.9000	0.1250	0.3750	0.4177	0.7111	0.9410	
	d	-0.7000	-0.3500	-0.0199	0.2000	0.4619	0.8605	1.0000	-0.7000	-0.3000	-0.0859	0.1402	0.4881	0.8881	0.9673	Null	Null	Null	Null	Null	
4	a	NC	-0.6824	-0.3988	-0.1743	0.0571	0.3418	0.7200	NC	-0.7157	-0.4371	-0.1441	0.0664	0.3276	0.7021	NC	0.1076	0.3071	0.5231	0.7119	0.0026
	b	NC	-0.5118	-0.2339	-0.0095	0.1367	0.3903	0.8734	NC	-0.5244	-0.2508	-0.1302	0.1414	0.4309	0.8538	NC	NC	NC	NC	NC	0.0019
	c	-0.8770	-0.4464	-0.1080	0.1437	0.2971	0.7287	0.9144	-0.8720	-0.3544	-0.1321	0.0707	0.2009	0.6538	0.9465	0.1221	0.2730	0.4961	0.7037	0.9493	
	d	-0.7445	-0.3161	-0.0392	0.1514	0.3772	0.8445	0.9836	-0.7900	-0.3183	-0.0418	0.1631	0.2966	0.8870	0.9519	Null	Null	Null	Null	Null	
5	a	NC	-0.7803	-0.3835	-0.1055	0.0976	0.3130	0.8285	NC	-0.7041	-0.4753	-0.1532	0.0760	0.3498	0.8489	NC	0.1035	0.2804	0.4784	0.7343	0.0036
	b	NC	-0.5238	-0.2722	-0.0392	0.1413	0.3610	0.8918	NC	-0.5128	-0.2431	-0.1164	0.1326	0.4423	0.8916	NC	NC	NC	NC	NC	0.0027
	c	-0.8347	-0.4465	-0.1151	0.1272	0.2567	0.6381	0.9066	-0.8473	-0.3672	-0.1462	0.0988	0.2390	0.6020	0.9276	0.0881	0.3690	0.4645	0.7103	0.8927	
	d	-0.7701	-0.3328	-0.0825	0.1213	0.3449	0.8833	0.9529	-0.7621	-0.3355	-0.0429	0.1240	0.4691	0.8497	0.9842	Null	Null	Null	Null	Null	
6	a	NC	-0.7878	-0.4146	-0.1931	0.0891	0.3094	0.8097	NC	-0.7125	-0.4820	-0.1158	0.1000	0.3100	0.7306	NC	0.1218	0.2539	0.4870	0.7252	0.9261
	b	NC	-0.5191	-0.2000	-0.1452	0.1115	0.4304	0.8500	NC	-0.5401	-0.2918	-0.1046	0.1000	0.3777	0.8678	NC	NC	NC	NC	NC	0.0027
	c	-0.8786	-0.3883	-0.1468	0.0500	0.2834	0.7248	0.9156	-0.8605	-0.3500	-0.1103	0.0538	0.3000	0.6229	0.9336	0.0992	0.3317	0.5322	0.7500	0.9546	
	d	-0.7000	-0.3373	-0.0651	0.1431	0.5000	0.8787	0.9847	-0.7256	-0.3306	-0.0985	0.1683	0.2500	0.8388	0.9858	Null	Null	Null	Null	Null	

Table 4.5: Continued

Controller		Position Data for the Membership Functions																Objective Functions				
		Position (Figure 2)																				
		Input (1): Story Drift								Input (2): Story Absolute Acceleration												
LN	N	SN	Z	SP	P	LP	LN	N	SN	Z	SP	P	LP	LV	MeV	NV	HV	MV	F(1)	F(2)		
7	a	NC	-0.8000	-0.3382	-0.1761	0.0957	0.2856	0.7769	NC	-0.7343	-0.3000	-0.1274	0.0911	0.3416	0.8500	NC	0.1178	0.3567	0.4580	0.7001	0.0028	10.0357
	b	NC	-0.5500	-0.2177	-0.1484	0.4304	0.4049	0.8500	NC	-0.5060	-0.2337	-0.1079	0.1111	0.4033	0.8500	NC	NC	NC	NC	NC	NC	NC
	c	-0.9000	-0.3956	-0.1000	0.0972	0.7248	0.6776	0.9000	-0.8355	-0.3500	-0.1453	0.1163	0.2327	0.7177	0.9443	0.1200	0.3045	0.5259	0.7500	1.0000	10.0028	
	d	-0.7662	-0.3355	-0.0157	0.1981	0.8787	0.8418	0.9951	-0.8000	-0.3161	-0.0968	0.1970	0.3590	0.9000	0.9500	Null	Null	Null	Null	Null	Null	Null
8	a	NC	-0.7292	-0.4554	-0.1163	0.0108	0.3500	0.7823	NC	-0.8000	-0.3427	-0.1000	0.0074	0.3500	0.7778	NC	0.0830	0.2500	0.4580	0.6670	0.0028	10.0813
	b	NC	-0.5500	-0.3000	-0.1358	0.1121	0.4500	0.9000	NC	-0.5025	-0.2006	-0.1100	0.1111	0.4125	0.9000	NC	NC	NC	NC	NC	NC	NC
	c	-0.8026	-0.4500	-0.1500	0.0635	0.2000	0.6825	0.9000	-0.8231	-0.4080	-0.1361	0.1500	0.2357	0.6000	0.9000	0.0988	0.3338	0.5410	0.6250	0.8750	0.0028	10.0813
	d	-0.7740	-0.3000	-0.0635	0.2000	0.4013	0.9000	1.0000	-0.7000	-0.3000	-0.0199	0.1000	0.2500	0.8000	1.0000	Null	Null	Null	Null	Null	Null	Null
9	a	NC	-0.7062	-0.3174	-0.1128	0.0707	0.3396	0.7615	NC	-0.7224	-0.3541	-0.1735	0.0017	0.3287	0.7748	NC	0.1032	0.3453	0.4892	0.7020	0.0058	0.0067
	b	NC	-0.5069	-0.2991	-0.0361	0.1049	0.3647	0.8709	NC	-0.5015	-0.2818	-0.1385	0.1381	0.3811	0.8517	NC	NC	NC	NC	NC	NC	NC
	c	-0.8944	-0.3600	-0.1003	0.0747	0.2636	0.6264	0.9087	-0.8068	-0.4481	-0.1012	0.1053	0.2995	0.6288	0.9138	0.1099	0.3051	0.5272	0.6822	0.8986	0.0058	0.0067
	d	-0.7482	-0.3443	-0.0870	0.1225	0.2947	0.8156	0.9506	-0.7814	-0.3040	-0.0640	0.1741	0.3285	0.8402	0.9856	Null	Null	Null	Null	Null	Null	Null
10	a	NC	-0.7534	-0.4623	-0.1072	0.0635	0.3117	0.8059	NC	-0.7003	-0.4012	-0.1941	0.0883	0.2890	0.7308	NC	0.1079	0.3285	0.4781	0.6942	0.0054	0.0071
	b	NC	-0.5122	-0.2032	-0.0327	0.1011	0.4257	0.8797	NC	-0.5134	-0.2229	-0.1445	0.1293	0.4202	0.8511	NC	NC	NC	NC	NC	NC	NC
	c	-0.8086	-0.3861	-0.1115	0.0992	0.2355	0.7125	0.9342	-0.8968	-0.3793	-0.1340	0.0517	0.2503	0.6282	0.9287	0.1080	0.3558	0.4260	0.7267	0.9918	0.0054	0.0071
	d	-0.7826	-0.3262	-0.0263	0.1299	0.2645	0.8708	0.9846	-0.7685	-0.3324	-0.0646	0.1064	0.2765	0.8949	0.9918	Null	Null	Null	Null	Null	Null	Null

* NC: Not calculated; the value is pre-defined.

** Null: Not specified parameter for the defined membership function.

* NC: Not calculated; the value is pre-defined.

** Null: Not specified parameter for the defined membership function.

Table 4.6: The Related Base Rules' Weights for the Fuzzy Logic Controllers (El Centro Earthquake)

<i>The Rules</i>		<i>The Rules' Weights Per Obtained Optimum Fuzzy Logic Controllers</i>									
The Condition (Table 1)	The Result	Controller #1	Controller #2	Controller #3	Controller #4	Controller #5	Controller #6	Controller #7	Controller #8	Controller #9	Controller #10
LN & LN	MV	0.9779	0.8573	0.0000	0.6608	0.5685	0.2489	0.2784	0.4561	0.5859	0.3277
LN & N	MV	0.4368	0.5220	0.2004	0.7233	0.9473	0.8441	0.6721	0.6523	0.0891	0.3594
LN & SN	HV	0.0953	0.2349	0.6365	0.7216	0.8126	0.1702	0.9247	0.8781	0.2735	0.0120
LN & Z	MV	0.2091	0.1725	0.4886	0.5666	0.5644	0.6554	0.4526	0.6407	0.7633	0.7002
LN & SP	MeV	0.4312	0.2593	0.2494	0.5687	0.1593	0.3965	0.5215	0.1317	0.1227	0.2353
LN & P	MeV	0.3361	0.8870	0.9646	0.6540	0.1927	0.0000	0.0327	0.1275	0.2610	0.7587
LN & LP	LV	0.8540	0.0511	0.4541	0.8180	0.3792	0.1954	0.8758	0.0082	0.1720	0.9114
N & LN	MV	0.7619	0.8065	0.9547	0.3835	1.0000	0.0756	1.0000	0.7669	0.8835	0.0406
N & N	HV	0.2062	0.1981	1.0000	0.4873	1.0000	0.0452	0.7372	0.5305	0.7088	0.8986
N & SN	NV	0.2375	0.0630	0.6334	0.6618	0.2585	0.1144	0.1318	0.5168	0.2287	0.2002
N & Z	NV	0.6143	0.5352	0.5905	0.3313	0.9409	0.2150	0.6164	0.0676	0.9689	0.5776
N & SP	MeV	0.0849	0.6036	0.8264	0.6909	0.6436	0.9324	0.3308	0.3961	0.2659	0.5711
N & P	MeV	0.7285	0.2433	0.3170	0.6527	0.6527	0.6979	0.0000	0.7679	0.2354	0.8766
N & LP	LV	0.0679	0.7197	0.6513	0.0057	0.3167	0.6506	0.0977	0.4698	0.9406	0.7711
SN & LN	NV	0.1123	0.4504	0.7688	0.4052	0.4537	0.8225	0.3686	0.8734	0.3622	0.2094
SN & N	NV	0.5440	1.0000	0.2316	0.6237	0.2884	0.0769	0.7645	0.4991	0.0504	0.9411
SN & SN	NV	0.3119	0.5511	0.2088	0.1585	0.5910	0.0000	0.0625	0.1795	0.7792	0.1754
SN & Z	MeV	0.1821	0.8063	0.3529	0.7575	0.7775	0.5703	1.0000	0.2427	0.7844	0.1986
SN & SP	LV	1.0000	0.0828	0.0849	0.0841	0.5413	0.4330	0.8264	0.7894	0.6288	0.2275
SN & P	LV	0.0000	0.3271	0.7015	0.7992	0.8380	0.8792	0.1636	0.3239	0.4158	0.0144
SN & LP	LV	0.8085	0.6258	0.7292	0.2643	0.0706	0.0374	0.3876	0.2392	0.6256	0.3858
Z & LN	MeV	0.0000	0.6462	0.2689	0.6946	0.0000	0.0181	0.1453	0.1258	0.9203	0.8516
Z & N	MeV	0.3102	0.1322	0.7671	0.5386	0.9504	0.9021	0.7508	0.9551	0.1954	0.0073
Z & SN	LV	0.8998	0.5063	0.2027	0.3169	0.2388	0.0000	0.7462	0.0930	0.3015	0.0776
Z & Z	LV	0.0000	0.0000	0.0219	0.0472	0.0000	0.2280	0.0401	0.1880	0.9426	0.0340
Z & SP	LV	0.3272	0.1656	0.2882	0.5399	0.4687	0.1079	0.6788	0.1803	0.9554	0.0360
Z & P	LV	0.8008	0.4829	0.1351	0.0271	0.4445	0.1234	0.3265	0.1821	0.3894	0.3972
Z & LP	LV	0.1345	0.9559	0.3917	0.2238	0.9950	0.4738	0.5303	0.2454	0.8106	0.7342
SP & LN	NV	0.5924	0.5911	0.9534	0.0235	0.3095	0.3022	0.4826	0.8950	0.1845	0.3897
SP & N	MeV	0.6038	0.0974	0.8246	0.3585	0.8218	0.5768	0.2111	0.4155	0.4221	0.0355
SP & SN	LV	0.2261	0.8937	0.5669	0.2211	0.0000	0.7099	0.5270	0.2748	0.1528	0.3156
SP & Z	LV	0.5417	0.6752	0.3313	0.1702	0.5938	0.3522	0.8416	0.2922	0.4184	0.4129
SP & SP	MeV	0.7350	0.5198	0.8589	0.7528	0.3432	0.3412	0.6090	0.3932	0.4556	0.8804
SP & P	NV	0.7771	0.8289	0.2868	0.9145	0.7743	0.3148	0.8105	0.5171	0.4664	0.0963
SP & LP	NV	0.6261	0.6951	0.9733	0.8349	0.9987	0.3046	0.3954	0.8054	0.6537	0.6265
P & LN	MeV	0.5085	0.5348	0.4858	0.6995	0.0000	0.0222	0.4977	0.6411	0.6267	0.9073

Table 4.6: Continued

<i>The Rules</i>		<i>The Rules' Weights Per Obtained Optimum Fuzzy Logic Controllers</i>									
<i>The Condition (Table 1)</i>	<i>The Result</i>	<i>Controller #1</i>	<i>Controller #2</i>	<i>Controller #3</i>	<i>Controller #4</i>	<i>Controller #5</i>	<i>Controller #6</i>	<i>Controller #7</i>	<i>Controller #8</i>	<i>Controller #9</i>	<i>Controller #10</i>
P & N	NV	0.0000	0.0684	0.6504	0.7534	0.5374	0.1296	0.7119	0.6893	0.6391	0.2748
P & SN	NV	0.7191	0.8107	0.8639	0.7904	0.0354	0.9082	1.0000	0.3008	0.4046	0.6956
P & Z	NV	0.1556	0.0324	0.1498	0.3789	0.0309	0.9872	0.0000	0.5085	0.1760	0.1411
P & SP	HV	0.6628	0.1309	0.7393	0.3436	0.7504	0.2258	0.9757	0.7080	0.1064	0.3106
P & P	HV	0.6543	0.8776	0.0000	0.6544	0.9923	0.5318	0.2056	0.4474	0.7528	0.3389
P & LP	MV	0.5387	0.8833	0.7282	0.8773	0.0693	0.3835	0.8313	0.6288	0.6967	0.0622
LP & LN	NV	0.1303	0.0148	0.3302	0.3430	0.2539	0.0554	0.8099	0.9052	0.9801	0.2174
LP & N	NV	0.9530	0.8194	0.5537	0.5181	0.0000	0.2226	0.4972	0.9470	0.1247	0.9695
LP & SN	HV	0.5720	0.4749	0.3996	0.9641	0.5484	0.7792	0.7508	0.8631	0.2214	0.4285
LP & Z	HV	0.9571	0.8618	0.7695	0.2462	0.7845	0.3900	0.7424	0.4703	0.7124	0.0895
LP & SP	HV	0.6440	0.8567	0.8226	0.3089	0.1401	0.4262	0.8943	0.4167	0.7449	0.0781
LP & P	MV	0.8302	0.5044	0.3010	0.7566	0.7319	0.7688	1.0000	0.3305	0.2635	0.5391
LP & LP	MV	0.5739	0.3727	0.6439	0.6299	0.8393	0.4048	0.5275	0.0246	0.7994	0.5613
Maximum Value Per Controller		1.0000	1.0000	1.0000	0.9641	1.0000	0.9872	1.0000	0.9551	0.9801	0.9695

Table 4.7: The related base rules' weights for the fuzzy logic controllers (Northridge Earthquake)

<i>The Rules</i>		<i>The Rules' Weights Per Obtained Optimum Fuzzy Logic Controllers</i>									
<i>The Condition (Table 1)</i>	<i>The Result</i>	<i>Controller #1</i>	<i>Controller #2</i>	<i>Controller #3</i>	<i>Controller #4</i>	<i>Controller #5</i>	<i>Controller #6</i>	<i>Controller #7</i>	<i>Controller #8</i>	<i>Controller #9</i>	<i>Controller #10</i>
LN & LN	MV	0.9779	0.8573	0.0000	0.5094	0.1458	0.5685	0.2489	0.2784	0.6155	0.8669
LN & N	MV	0.4368	0.5220	0.2004	0.5538	0.9316	0.9473	0.8441	0.6721	0.3217	0.5151
LN & SN	HV	0.0953	0.2349	0.6365	0.0146	0.5693	0.8126	0.1702	0.9247	0.4014	0.6529
LN & Z	MV	0.2091	0.1725	0.4886	0.7343	0.7946	0.5644	0.6554	0.4526	0.7367	0.8572
LN & SP	MeV	0.4312	0.2593	0.2494	0.4472	0.9132	0.1593	0.3965	0.5215	0.2719	0.3770
LN & P	MeV	0.3361	0.8870	0.9646	0.2240	0.6003	0.1927	0.0000	0.0327	0.2214	0.9170
LN & LP	LV	0.8540	0.0511	0.4541	0.6678	0.1189	0.3792	0.1954	0.8758	0.5164	0.5039
N & LN	MV	0.7619	0.8065	0.9547	0.2291	0.7126	1.0000	0.0756	1.0000	0.7391	0.7319
N & N	HV	0.2062	0.1981	1.0000	0.8371	0.0499	1.0000	0.0452	0.7372	0.8940	0.2686
N & SN	NV	0.2375	0.0630	0.6334	0.0917	0.3839	0.2585	0.1144	0.1318	0.6557	0.1792
N & Z	NV	0.6143	0.5352	0.5905	0.1267	0.0910	0.9409	0.2150	0.6164	0.1665	0.6015

Table 4.7: Continued

The Rules		The Rules' Weights Per Obtained Optimum Fuzzy Logic Controllers									
The Condition (Table 1)	The Result	Controller #1	Controller #2	Controller #3	Controller #4	Controller #5	Controller #6	Controller #7	Controller #8	Controller #9	Controller #10
N & SP	MeV	0.0849	0.6036	0.8264	0.7128	0.3148	0.6436	0.9324	0.3308	0.3296	0.7022
N & P	MeV	0.7285	0.2433	0.3170	0.1889	0.6781	0.6527	0.6979	0.0000	0.4931	0.0126
N & LP	LV	0.0679	0.7197	0.6513	0.5277	0.0916	0.3167	0.6506	0.0977	0.1671	0.2738
SN & LN	NV	0.1123	0.4504	0.7688	0.2025	0.0775	0.4537	0.8225	0.3686	0.1278	0.6529
SN & N	NV	0.5440	1.0000	0.2316	0.0070	0.9976	0.2884	0.0769	0.7645	0.2889	0.6823
SN & SN	NV	0.3119	0.5511	0.2088	0.3736	0.6966	0.5910	0.0000	0.0625	0.4714	0.0212
SN & Z	MeV	0.1821	0.8063	0.3529	0.0933	0.3796	0.7775	0.5703	1.0000	0.4669	0.7149
SN & SP	LV	1.0000	0.0828	0.0849	0.0450	0.0986	0.5413	0.4330	0.8264	0.1009	0.5132
SN & P	LV	0.0000	0.3271	0.7015	0.3144	0.9816	0.8380	0.8792	0.1636	0.7029	0.6307
SN & LP	LV	0.8085	0.6258	0.7292	0.7575	0.8935	0.0706	0.0374	0.3876	0.9681	0.9672
Z & LN	MeV	0.0000	0.6462	0.2689	0.6291	0.8976	0.0000	0.0181	0.1453	0.3137	0.6804
Z & N	MeV	0.3102	0.1322	0.7671	0.7194	0.3683	0.9504	0.9021	0.7508	0.3650	0.0449
Z & SN	LV	0.8998	0.5063	0.2027	0.7484	0.2052	0.2388	0.0000	0.7462	0.2709	0.7652
Z & Z	LV	0.0000	0.0000	0.0219	0.3795	0.2036	0.0000	0.2280	0.0401	0.9488	0.3578
Z & SP	LV	0.3272	0.1656	0.2882	0.1463	0.5480	0.4687	0.1079	0.6788	0.0544	0.9965
Z & P	LV	0.8008	0.4829	0.1351	0.8720	0.4564	0.4445	0.1234	0.3265	0.7711	0.5905
Z & LP	LV	0.1345	0.9559	0.3917	0.7015	0.7424	0.9950	0.4738	0.5303	0.0194	0.3084
SP & LN	NV	0.5924	0.5911	0.9534	0.6313	0.7590	0.3095	0.3022	0.4826	0.3554	0.8117
SP & N	MeV	0.6038	0.0974	0.8246	0.9244	0.5970	0.8218	0.5768	0.2111	0.2879	0.5796
SP & SN	LV	0.2261	0.8937	0.5669	0.5452	0.4510	0.0000	0.7099	0.5270	0.3520	0.2095
SP & Z	LV	0.5417	0.6752	0.3313	0.8126	0.8270	0.5938	0.3522	0.8416	0.9471	0.5220
SP & SP	MeV	0.7350	0.5198	0.8589	0.2196	0.2419	0.3432	0.3412	0.6090	0.1395	0.8696
SP & P	NV	0.7771	0.8289	0.2868	0.8437	0.3747	0.7743	0.3148	0.8105	0.3880	0.2504
SP & LP	NV	0.6261	0.6951	0.9733	0.1924	0.9367	0.9987	0.3046	0.3954	0.9026	0.3718
P & LN	MeV	0.5085	0.5348	0.4858	0.6962	0.4896	0.0000	0.0222	0.4977	0.4424	0.3226
P & N	NV	0.0000	0.0684	0.6504	0.0800	0.0326	0.5374	0.1296	0.7119	0.7266	0.9321
P & SN	NV	0.7191	0.8107	0.8639	0.3913	0.9522	0.0354	0.9082	1.0000	0.3189	0.2091
P & Z	NV	0.1556	0.0324	0.1498	0.8633	0.8956	0.0309	0.9872	0.0000	0.1602	0.6739
P & SP	HV	0.6628	0.1309	0.7393	0.0294	0.7538	0.7504	0.2258	0.9757	0.3811	0.6480
P & P	HV	0.6543	0.8776	0.0000	0.0657	0.0212	0.9923	0.5318	0.2056	0.0096	0.9820
P & LP	MV	0.5387	0.8833	0.7282	0.0600	0.7290	0.0693	0.3835	0.8313	0.1472	0.4412
LP & LN	NV	0.1303	0.0148	0.3302	0.7465	0.3044	0.2539	0.0554	0.8099	0.5141	0.4759
LP & N	NV	0.9530	0.8194	0.5537	0.6081	0.7118	0.0000	0.2226	0.4972	0.6307	0.7782
LP & SN	HV	0.5720	0.4749	0.3996	0.3783	0.6043	0.5484	0.7792	0.7508	0.7231	0.6502
LP & Z	HV	0.9571	0.8618	0.7695	0.2200	0.8735	0.7845	0.3900	0.7424	0.8470	0.0982
LP & SP	HV	0.6440	0.8567	0.8226	0.3581	0.6127	0.1401	0.4262	0.8943	0.0836	0.8375
LP & P	MV	0.8302	0.5044	0.3010	0.3234	0.3511	0.7319	0.7688	1.0000	0.5718	0.7212
LP & LP	MV	0.5739	0.3727	0.6439	0.6167	0.1136	0.8393	0.4048	0.5275	0.5034	0.8255
Maximum Value Per Controller		1.0000	1.0000	1.0000	0.9244	0.9976	1.0000	0.9872	1.0000	0.9681	0.9965

The maximum structural response for the system controlled by different strategies under the effect of different excitations are shown in Figure 4.15 and Table 4.8. Online-FLMVOC algorithm has reduced the first-story relative displacement by 74% and 45% in comparison with the uncontrolled response under the effect of El Centro and Northridge earthquakes, respectively; meanwhile, the reduction in story drift for the other floors is of an average of 66% and 33%, respectively. The absolute first-story acceleration reduction is 60% and 26 % under the effect of El Centro and Northridge earthquakes, respectively. However, a higher reduction is noted in the third-floor acceleration response at 72% and 35%, respectively, which proves the system's capability to dissipate the energy on the first floor and control the story acceleration without worsening its performance against the story displacement response.

Comparing with the performance of different vibration control strategies, namely Offline-FLMVOC, Modified Quasi Bang-Bang (MBB), and LQR-Clipped Optimal (CO), Online-FLMVOC exhibited a highly competitive performance of response control actions that is similar to the other strategies. Online-FLMVOC successfully demonstrated adaptive characteristics, allowing for the achievement of identical performance to Offline-FLMVOC in real-time. This highlights the effectiveness of the Online-FLMVOC approach in achieving and sustaining an optimal real-time Fuzzy Logic Controller (FLC) that shows remarkable performance when compared to other well-known control strategies. Furthermore, Online-FLMVOC demonstrated its dominance over MBB by decreasing the third-story drift by 34%, compared to only 19% for the system subjected to a near-field earthquake (Northridge). This finding illustrates the robustness of the proposed system in efficiently addressing uncertainties of external dynamic load. Figures 4.16 and 4.17 show the percentage reduction in the response of third floor achieved by the considered control strategies. The real-time responses for the considered control algorithms are shown in Figure 4.18 and Figure 4.19.

The real-time voltage and control force for the MR damper commanded by the developed Online-FLMVOC and other considered vibration control strategies are shown in Figure 4.20 and Figures 4.21-4.22. The maximum control voltage utilized by the Online-FLMVOC is 1.416 V and 1.379 V, which produced a maximum control force of 722.8 N and 632.3 N when subjected to El Centro and Northridge earthquakes, respectively. Better performance in managing the MR energy is noted for Online-FLMVOC in comparison with Offline version, where the last is allocated more energy to manipulate the same performance. Online-FLMVOC achieved efficient control action by utilizing only 45-66% of the control force produced by MBB and CO strategies. This demonstrates the superiority of the developed system in terms of power-saving and adaptive management of the power resources without compromising the performance of the response control. However, this behaviour is expected to be further enhanced by utilizing higher-order Fuzzy Logic membership functions.

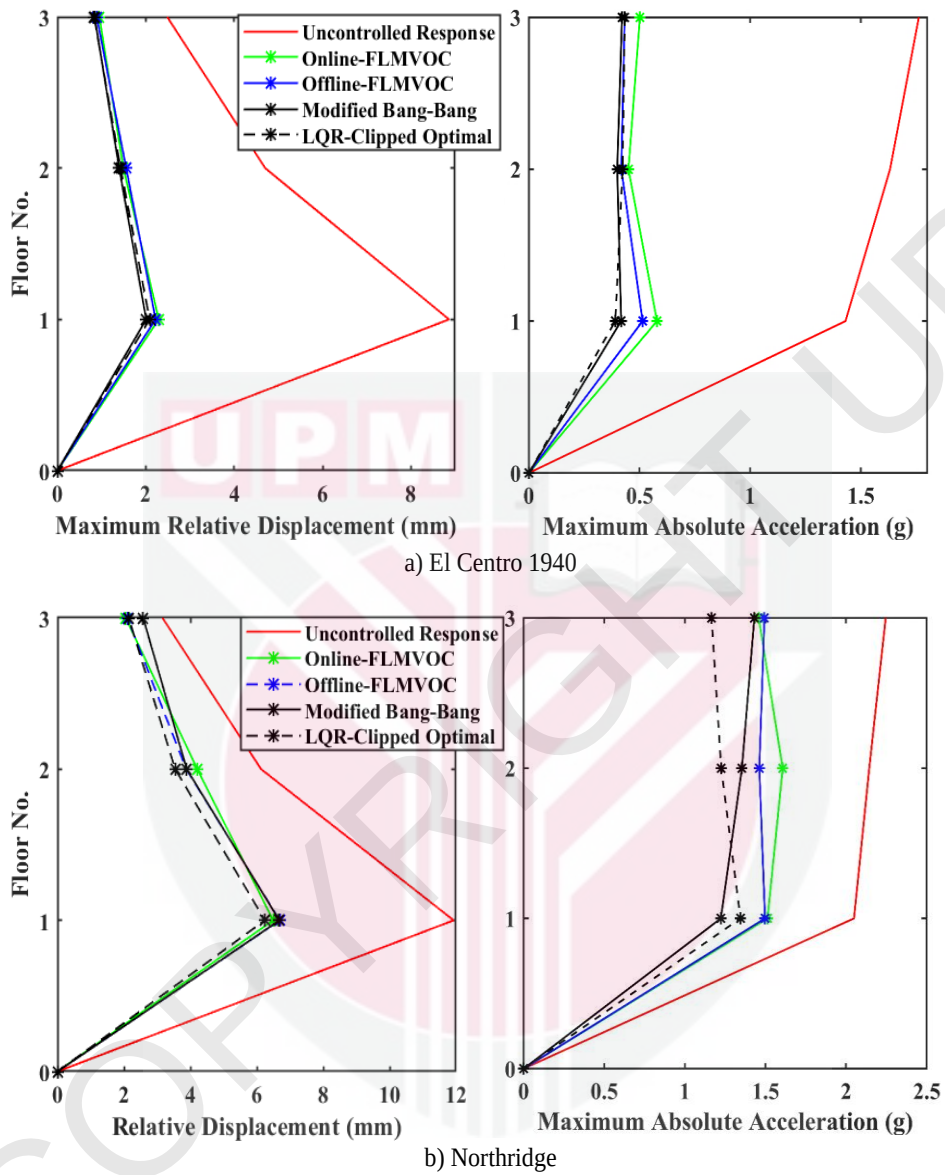


Figure 4.15: Maximum structural response

Table 4.8: Maximum floors' response compared with reference control strategies

<i>Earthquake</i>	<i>El Centro 1940</i>			<i>Northridge</i>		
	<i>Story Drift (m)*</i>	<i>Story Acce.(m/s²)</i>	<i>Control Force(N)</i>	<i>Story Drift (m)</i>	<i>Story Acce.(m/s²)</i>	<i>Control Force(N)</i>
Un-Controlled	8.900E-03	1.404E+01		1.190E-02	2.010E+01	
	4.700E-03	1.601E+01	-	6.100E-03	2.103E+01	-
	2.500E-03	1.729E+01		3.200E-03	2.203E+01	
Offline-FLMVOC	2.200E-03	5.043E+00		6.700E-03	1.469E+01	
	1.600E-03	4.098E+00	744.18	3.900E-03	1.434E+01	742.67
	9.000E-04	4.245E+00		2.100E-03	1.465E+01	
Online-FLMVOC	2.300E-03	5.680E+00		6.500E-03	1.485E+01	
	1.500E-03	4.416E+00	722.83	4.200E-03	1.577E+01	632.35
	9.000E-04	4.923E+00		2.100E-03	1.431E+01	
Modified quasi-Bang-Bang	2.000E-03	4.091E+00		6.700E-03	1.200E+01	
	1.400E-03	3.916E+00	1092.80	3.900E-03	1.328E+01	1325.60
	8.430E-04	4.127E+00		2.600E-03	1.404E+01	
LQR-Clipped Optimal	2.100E-03	3.832E+00		6.200E-03	1.319E+01	
	1.400E-03	4.156E+00	1088.20	3.500E-03	1.203E+01	1392.50
	8.330E-04	4.250E+00		2.100E-03	1.144E+01	

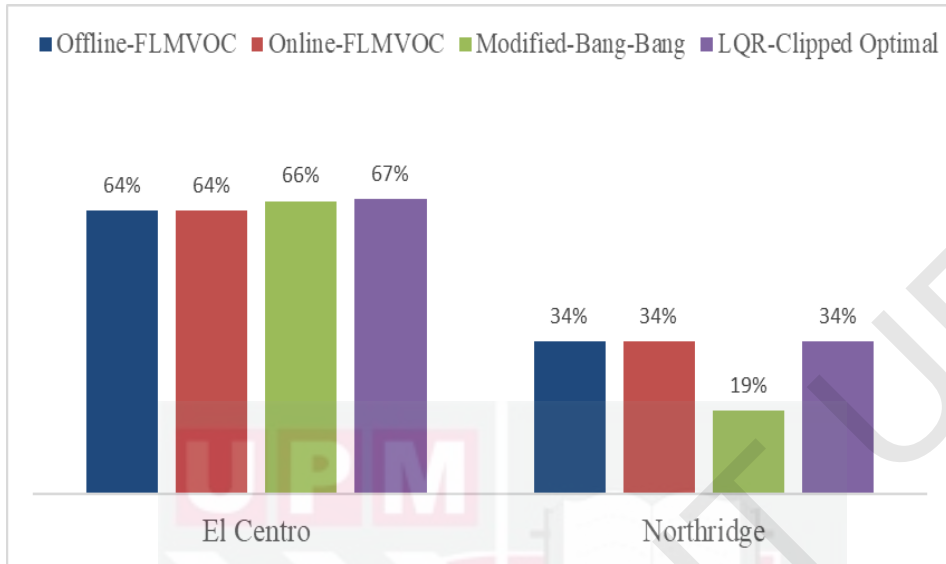


Figure 4.16: Third floor drift reduction by the considered control strategies

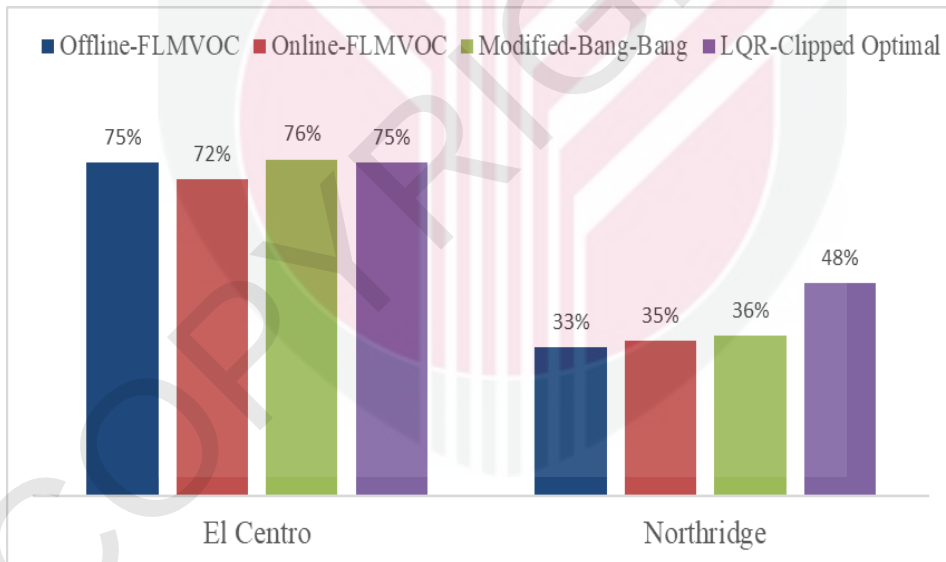


Figure 4.17: Third floor acceleration reduction by the considered control strategies

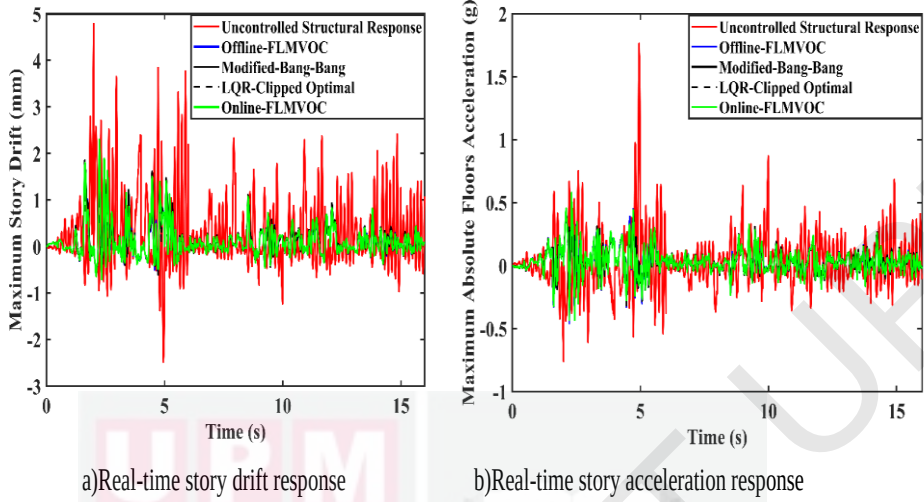


Figure 4.18: Real-time structural response (El Centro 1940 Earthquake)

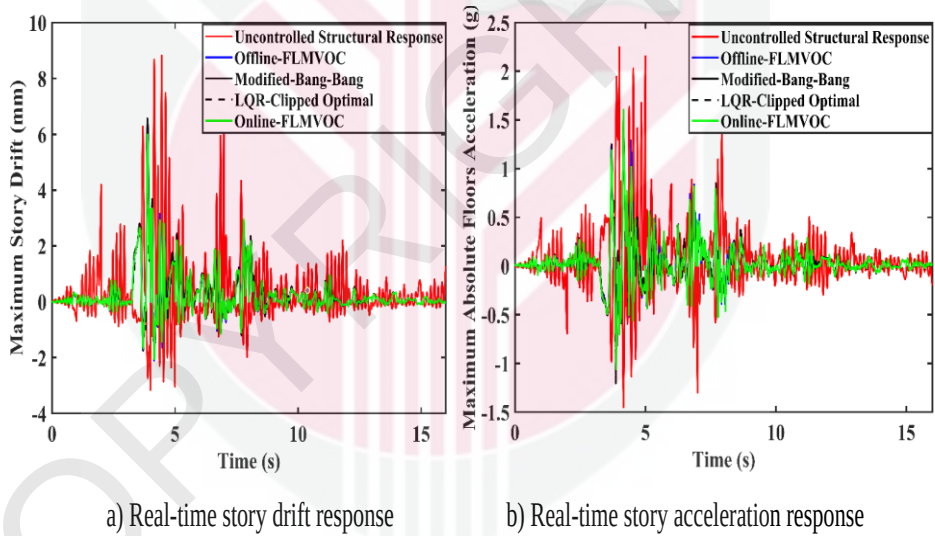


Figure 4.19: Real-time structural response (Northridge Earthquake)

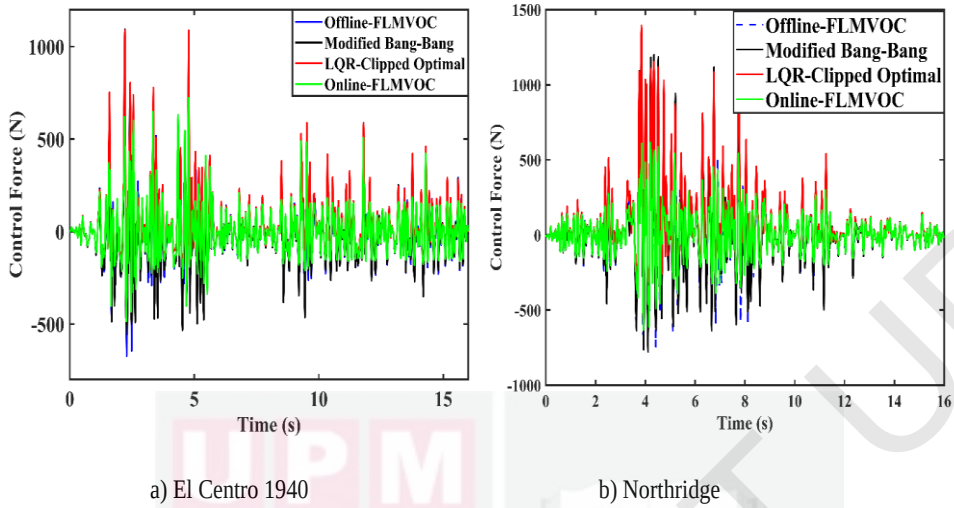


Figure 4.20: Real-time commanded control force

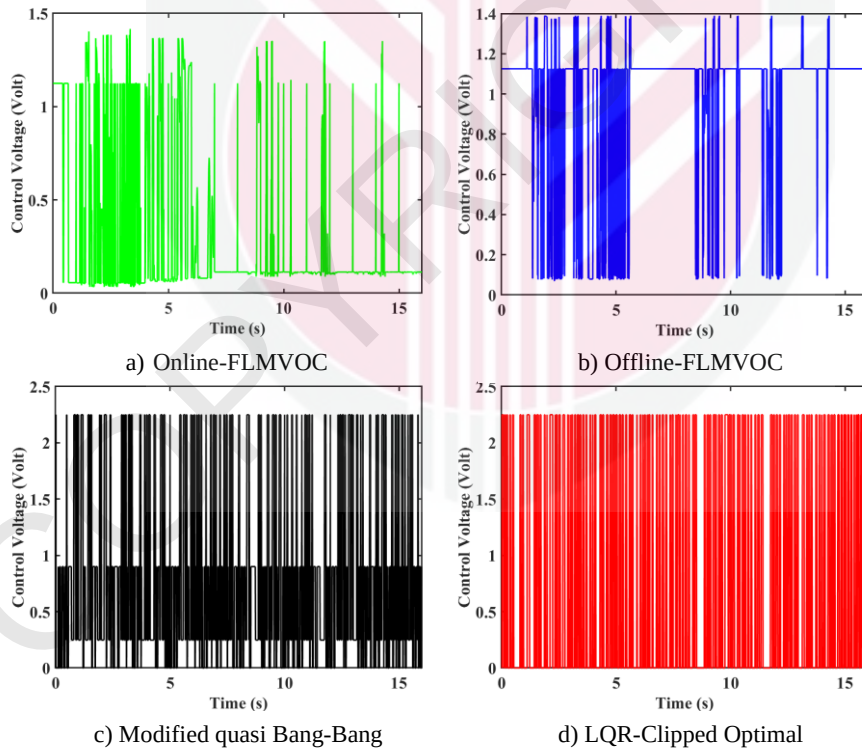


Figure 4.21: Real-time commanded voltage for the considered control strategies (El Centro 1940 Earthquake)

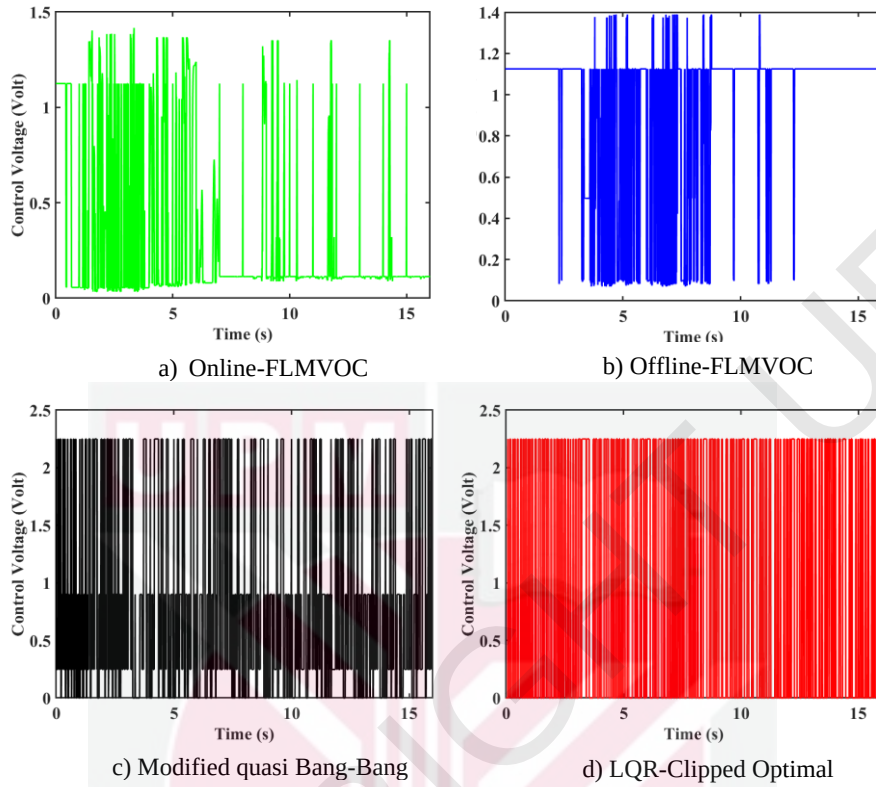


Figure 4.22: Real-time commanded voltage by the considered control strategies (Northridge Earthquake)

4.2.2 Wind-excited Structure

This section discusses the simulation results for the developed Online-FLMVOC implemented in a wind-prone high-rise building.

Figure 4.23 shows the initial FL controllers in the FIS memory. The initial controllers represent the Pareto optimal solutions from the Offline-FLMVOC.

The decentralized system concept was applied so that the structure in each considered direction responds independently. Figure 4.24 shows the produced FL controllers in the FIS memory for both subsystems (Along-Wind and Across-Wind vibration control system). It can be seen the development of FL Controllers during the simulation. The controllers are smartly sorted ascendingly (giving high priority to the controllers with minimum desired objective function) in the FIS memory according to the best acceleration control action, which is the desired action for wind- induced structure.

However, the developed FL controllers are almost similar in their characteristics and performance, which reflect the regular oscillation of wind load.

Figures 4.25-4.30 show the real-time structural response and compare it with the response of the uncontrolled structure (the structure without a vibration control system) and the structure controlled by Offline-FLMVOC.

The maximum structural response to the wind load time history is listed in Table 4.9. The outstanding performance of the developed algorithm to mitigate the across-wind excitation is indicated in Figure 4.25, which represents the most critical problem for the studied structure. Online-FLMVOC has reduced the maximum floor displacement by 34% of the uncontrolled response, Table 4.9. Contrary, Offline-FLMVOC has failed to control the response effectively.

Table 4.9: Maximum structural response

Vibration Control Algorithm	Displacement			Acceleration			Velocity
	Across-Wind	Along-Wind	Rotational	Across-Wind	Along-Wind	Rotational	Rotational
	(mm)	(mm)	(mrad)	(cm/s ²)	(cm/s ²)	(mrad/s ²)	(mrad/s)
Uncontrolled Case	84.9679	422.2482	0.0080	5.5161	19.7508	0.0366	0.0091
Offline-FLMVOC	242.5996	280.6843	0.0071	12.1061	19.2958	0.0770	0.0778
Online-FLMVOC	56.0832	363.4265	0.0075	7.2110	19.3552	0.0824	0.0414
Reduction Percentage	34%	14%	5%	NC	NC	NC	NC

The main advantage of Online-FLMVOC is the independency of the optimization process on the offline-data, instead, it continuously develops a new FLC controllers with the develop of the applied excitations, stimulating feedforward technique which ensure more adaptivity. Although Offline-FLMVOC showed a better control action against along-wind load than Online-FLMVOC, the latter has progressively developed a better action with increased excitation magnitude (refer to Figure 3.24), which reflects a more reasonable performance (Figure 4.26).

The same performance is obviously indicated in Figure 4.27 for the real-time rotational displacement response.

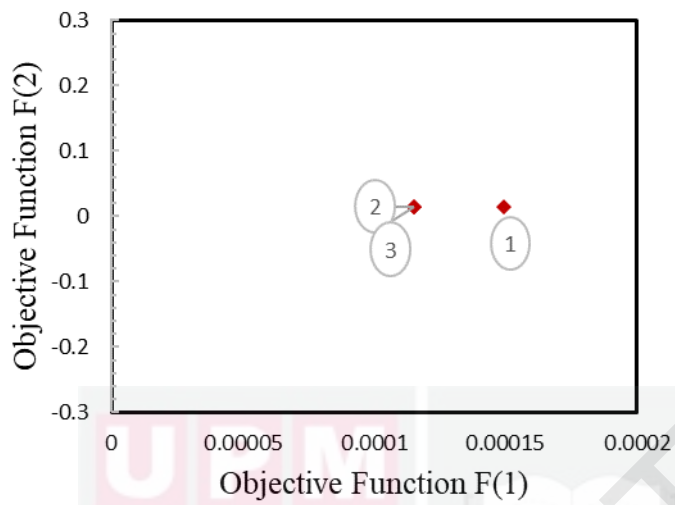


Figure 4.23: Initial FL controllers fed-in FIS memory

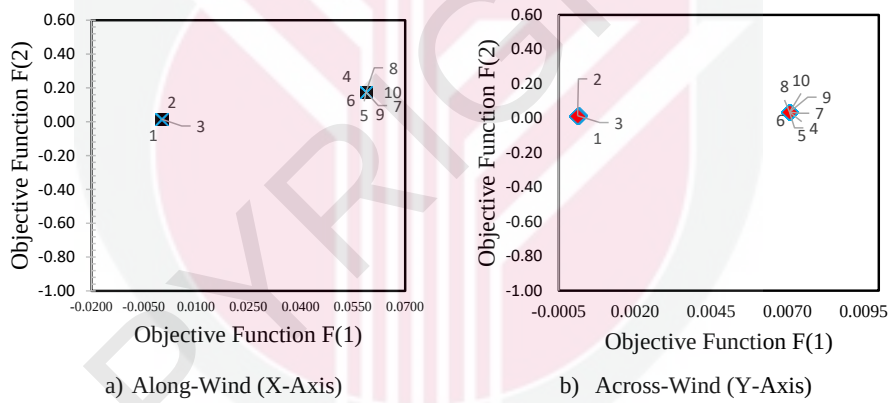


Figure 4.24: The obtained FL controllers in FIS memory

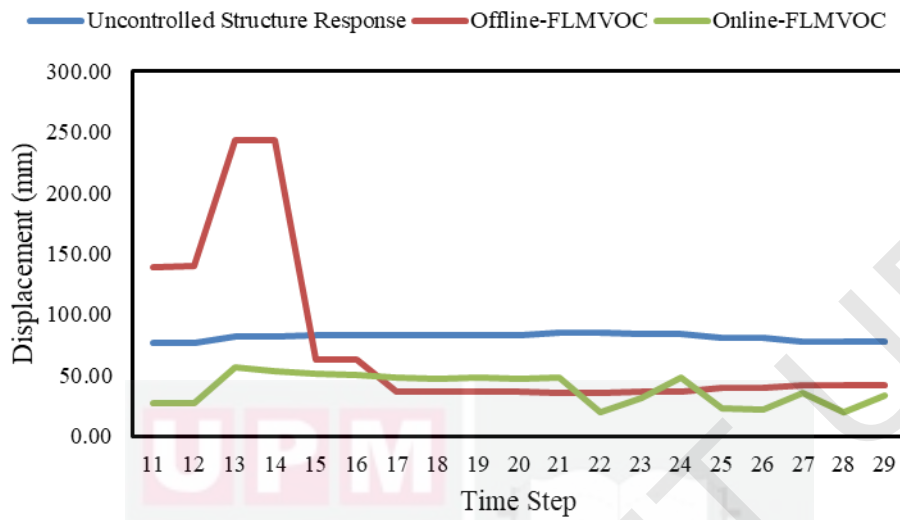


Figure 4.25: Displacement response for the 75th floor (Across-Wind)

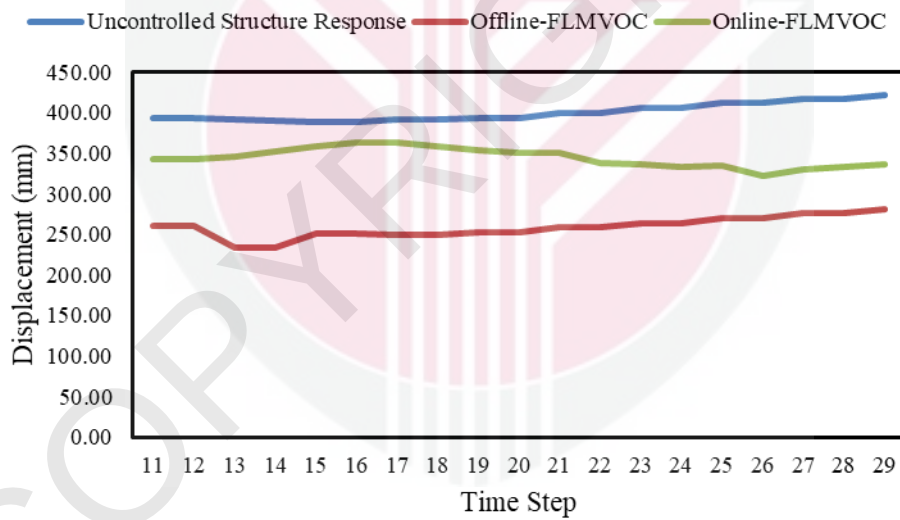


Figure 4.26: Displacement response for the 75th floor (Along-Wind)

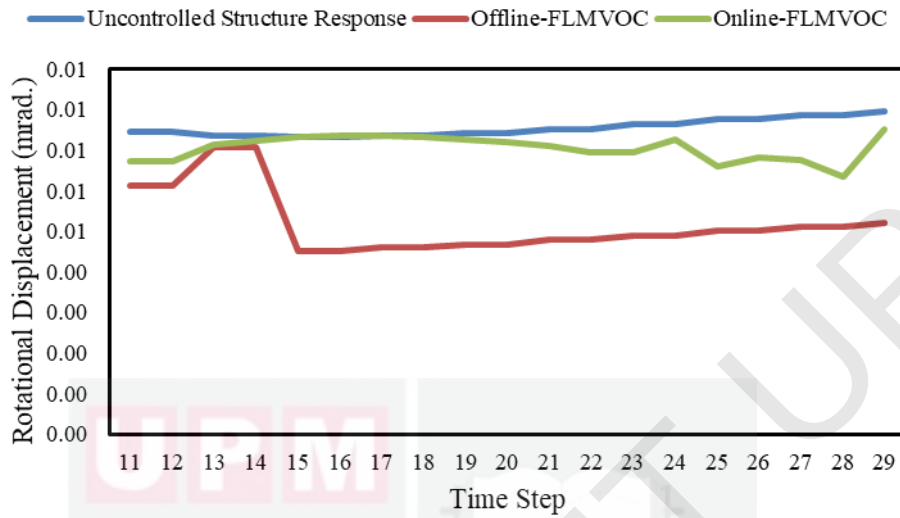


Figure 4.27: Rotational displacement response for the 75th floor

In terms of floor acceleration, the figures 4.28, 4.29 and 4.30 revealed a superior performance of Online-FLMVOC compared with Offline-FLMVOC by managing the control action and minimizing the acceleration response below the occupant comfort limit (0.2g) [91] without violating the control performance against displacement response.

Moreover, Online-FLMVOC showed the ability to control the fluctuation of across-wind acceleration albeit the diversity of acceleration magnitudes between across-wind and along-wind response, Figure 4.22. The same performance is evident in Figure 4.23 for along-wind acceleration response. Despite the asymmetric characteristics of the considered structure and vibration control system, the developed algorithm has been showing outstanding control action along the two main response directions without yielding a substantial increase in the magnitude of the torsional response (Figures 4.21 and 4.24).

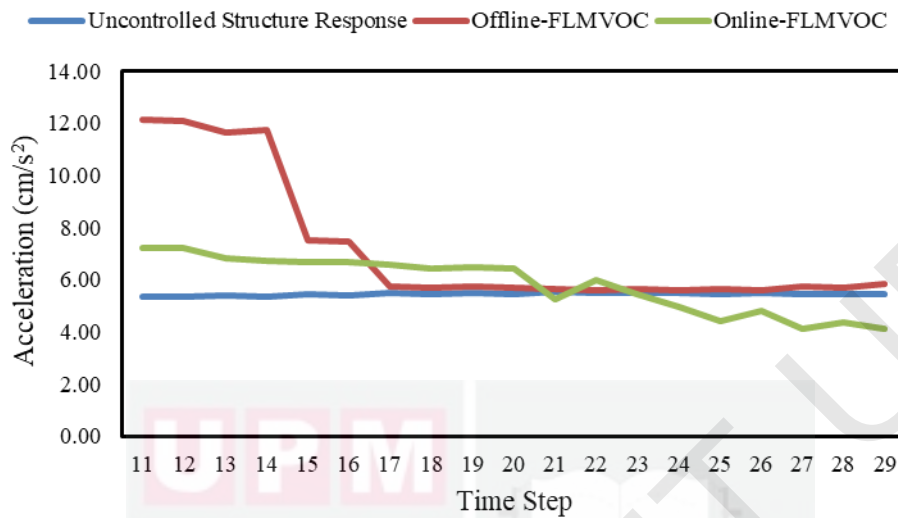


Figure 4.28: Acceleration response for the 75th floor (Across-Wind)

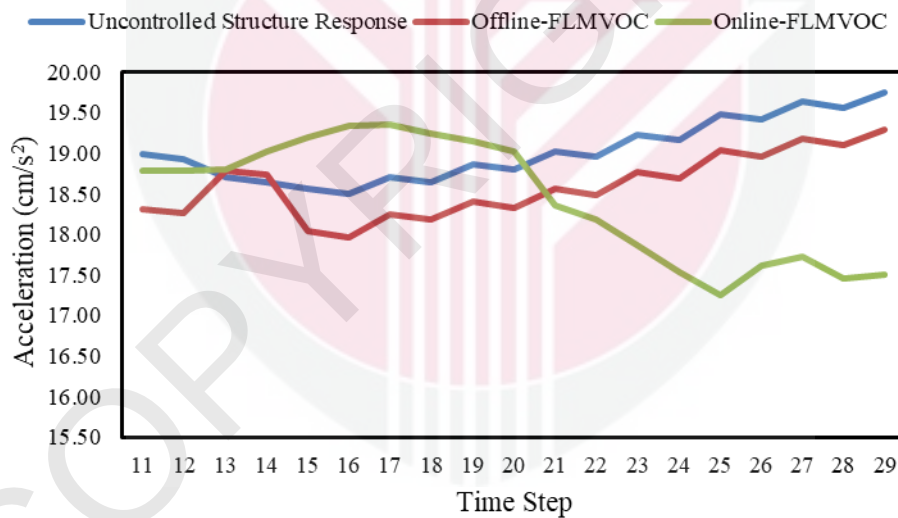


Figure 4.29: Acceleration response for the 75th floor (Along-Wind)

Returning to Table 4.9, the rotational velocity, which has been suggested by the ATC Guide 3 [91] as a new serviceability design criterion, has remained within the serviceability limit (5 mrad/s). Compared with Offline-FLMVOC, Online-FLMVOC controlled the torsional velocity more effectively, producing a maximum value of 0.0414 (mrad/s).

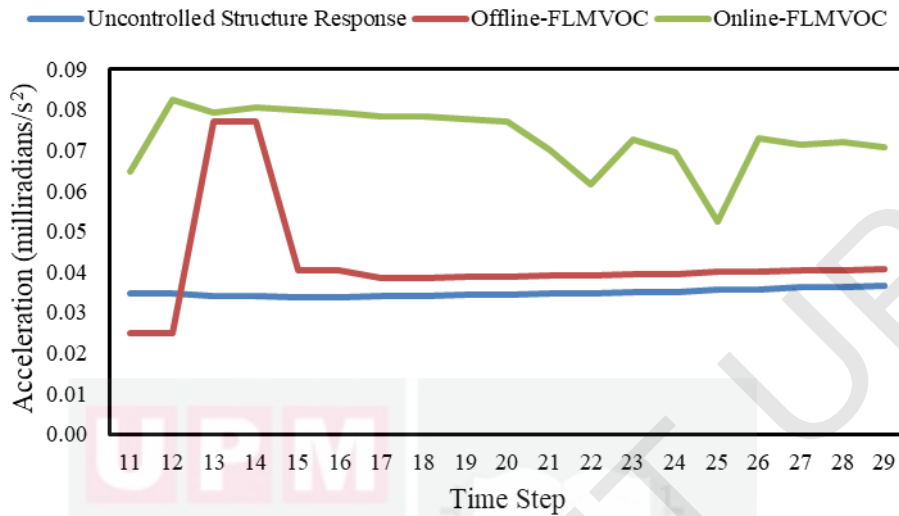


Figure 4.30: Rotational acceleration for the 75th floor

The superiority of Online-FLMVOC is noticeable by reviewing the results in Figures 4.31 and 4.32, which present the maximum control force generated by the MR dampers and the maximum commanding voltage generated by the FL controllers, respectively, especially in terms of across-wind response.

The maximum commanding voltage and control force generated against along-wind load are similar for both Online-FLMVOC and Offline-FLMVOC. However, a big difference between the two algorithm performances is noted for the across-wind load. Online-FLMVOC has produced a very effective control action by allocating 74% and 64% of corresponding Offline-FLMVOC commanding voltage and control forces, respectively.

Although the destabilizing action is not expected in semi-active vibration control systems as such systems do not consist of external actuators to generate the control forces, commanding over-required voltage to MR damper increases its stiffness and consequently changes the dynamic structural properties. In contrast to Offline-FLMVOC, Online-FLMVOC has adaptively avoided such undesired performance by real-time optimization and evaluating techniques.

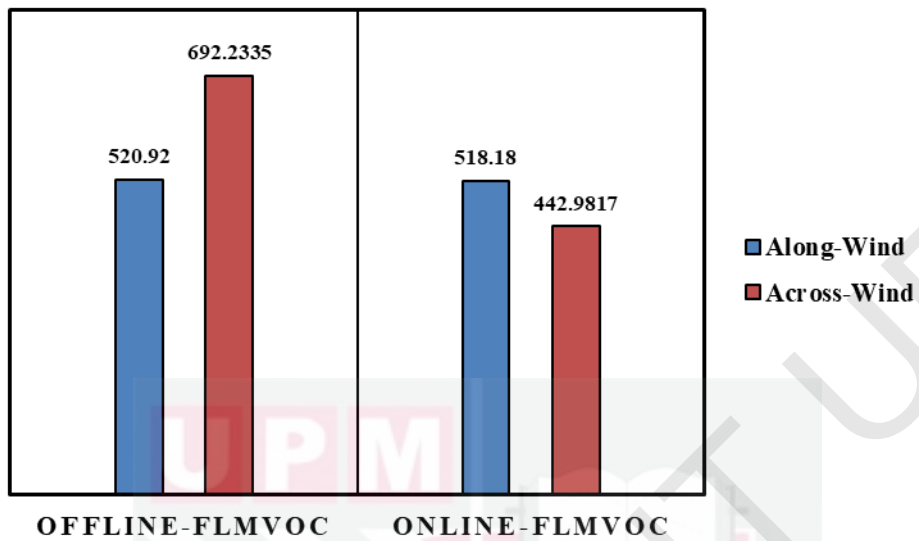


Figure 4.31: Maximum MR control force (kN/damper)

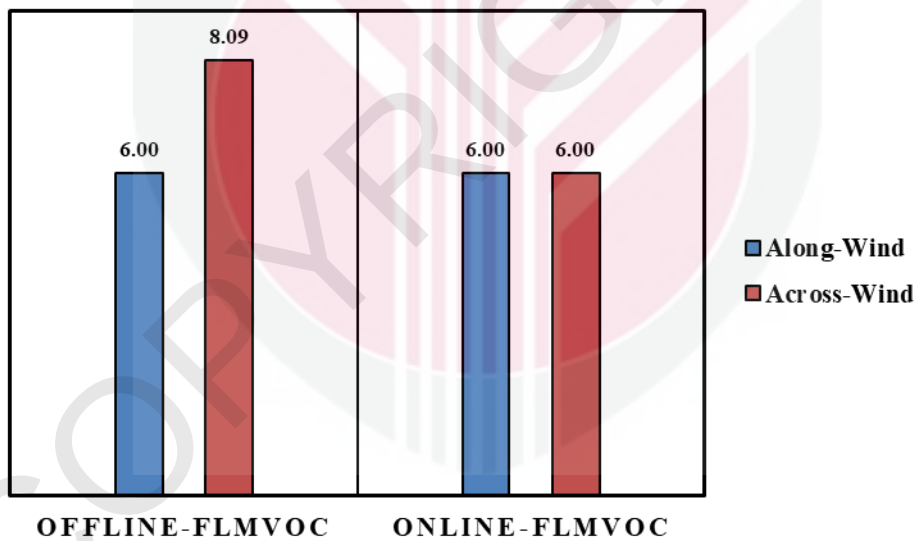


Figure 4.32: Maximum commanding voltage for MR dampers (volt/damper)

4.3 Summary

This chapter describes the assessment of both versions of proposed Fuzzy Logic Multi Verse Optimal control systems for building structures under the effect of seismic and wind loads. The results showed that FLMVOC was successful in suppressing the building's response under low and high peak ground acceleration. The algorithm was also efficient in controlling the high-rise building's movement under the effect of multi-attack angle wind load.

The developed FLMVOC demonstrated a superior performance with minimum energy consumption and effective control force in comparing with reference control strategy from literature.

The proposed algorithm was further improved by integrating it with a new data updating and FIS selection strategy to achieve targeted real-time adaptive response of the vibration control system, which was assessed by applying it to a three-story shear building subjected to different natural earthquakes and a full degree of freedom 76-story wind-sensitive building under the effect of three wind load components.

The results showed a more efficient control performance comparing with basic version of FLMVOC and other reference control strategy.

Moreover, Online-FLMVOC reduced the across-wind displacement without violating the torsional structural response, making it an efficient and robust control action against across-wind excitation, which is a critical problem for wind-sensitive structures.

CHAPTER 5

CONCLUSION AND FUTURE STUDIES

5.1 Conclusion

Recently, researchers and engineers showed enthusiasm and interest in employing semi-active damper systems to mitigate the vibration of structures subjected to external excitation, such as seismic and wind load, due to their effective performance. Traditional vibration dissipation systems have limited capacity to withstand uncertainties in external load patterns and the resulting changes in structural behavior. The robustness of existing semi-active vibration control systems to manage multi-component and multidirectional structural response interactions has not been thoroughly investigated. The conflicting nature of story drift and story acceleration, where an improvement in one could lead to a deterioration in the other, underscores the importance of developing an adaptive control system capable of managing both. Model-based control algorithms, such as LQR and LQG-based algorithms, have limited adaptability in terms of reliability and robustness due to their reliance on explicit definitions of structural properties. Therefore, this research has adopted to address the problems above by developing a new semi-active structural vibration control system (FLMVOC) then assessing its performance and robustness in mitigating the structural response under the effect of different earthquakes amplitudes and multi-attack angle wind load.

For this purpose, MATLAB program is integrated with a finite element package through oAPI interface to implement multiverse optimization algorithm and fuzzy logic system to perform semi-active vibration control of structures during applied excitation. A magnetorheological damper device has been implemented in this study as a semi-active device due to its high performance and quick action.

The performance of the proposed semi-active vibration control system is assessed by applying it to a three-story shear building subjected to different actual earthquakes. The results revealed a successful and competitive performance of the proposed algorithm in suppressing the building's response under the effect of low and high peak ground acceleration, which depicts the robustness of the proposed semi-active vibration system with an average reduction of story drift and story acceleration in the range of 51% and 22%, respectively. Moreover, the robustness of the developed system under the effect of multi-component excitation has been examined by implementing it in a high-rise building excited by wind load. The results showed an efficient control performance applied by the developed control algorithm via MR Damper to keep the structure within allowable limits of movement (deformation) and resident comfort criteria. Despite the difference between story acceleration and story drift, the proposed optimal controller exhibited a good ability to reduce each of them without amplifying the other. This can be seen in different load patterns. Moreover, FLMVOC showed similar performance in reducing acceleration and displacement response by 12% to 16% under

the effect of multi-attack angle wind load. Considering the energy consumption and control system resources management, the developed FLMVOC demonstrated a super performance with minimum energy consumption and effective control force by avoiding the saturation state (i.e., the increase in commanding voltage does not improve the controlling force) of the MR damper device. FLMVOC demonstrated exceptional power-saving capabilities by utilizing approximately 2V of the MR damper's current capacity. Therefore, FLMVOC presented a very promising and competitive model-free vibration control system that can control the structural response with uncertainties in both structural and excitation properties. However, it is also revealed that the optimal controller rationally depends on the load pattern utilized during the offline optimization process.

Therefore, the work is extended to develop a new version of FLMVOC (Online-FLMVOC) by integrating it with a new developed data updating and FIS selection strategies to achieve the targeted real-time adaptive response of the vibration control system. The performance of the proposed Online adaptive semi-active vibration control system is assessed by applying it to a three-story shear building subjected to different natural earthquakes.

The results revealed a successful and competitive performance of the proposed vibration control system in comparing with other well-known vibration control strategies to suppress the building's response under the effect of low and high peak ground acceleration. Average reduction of story drift and story acceleration are in range of 38% ~74% and 35% ~ 72% respectively. Moreover, Online-FLMVOC achieved the same control action as Modified quasi Bang-Bang (MBB) and Clipped Optimal (CO) control algorithms using only 45% ~ 66% of the relevant control force.

The robustness of the developed system has been examined by implementing it with a full degree of freedom 76-story wind-sensitive building under the effect of three wind load components. The results showed a more efficient control performance applied by Online-FLMVOC via MR Damper compared with FLMVOC.

Moreover, the developed control system showed a very efficient control action against the across-wind excitation, which represents the most critical problem for the studied structure. Online-FLMVOC reduced the across-wind displacement by 34% without violating the torsional structural response which depicts its reliability and robustness. Considering the energy consumption and control system resources management, the developed Online-FLMVOC demonstrated a super performance with minimum energy usage and effective control force in comparing with reference algorithms. Therefore, Online-FLMVOC presented a promising and competitive adaptive model-free control strategy that can control the structural response with uncertainties in both structural and excitation properties.

In summary, the developed FLMVOC and Online-FLMVOC have effectively addressed all research problems, showcasing highly competitive vibration control systems capable of adapting to external excitations, regardless of variations in the structure's type and properties. These systems successfully mitigate displacement and acceleration responses in the structure, despite their divergent actions. Importantly, these non-model-based control strategies eliminate the need for explicitly defining parameters of structural and damper properties, allowing for implementation across a wide array of structures without requiring offline adjustments or training.

Moreover, Online-FLMVOC exhibits superior adaptability compared to FLMVOC. The former achieves this by developing and employing optimal controllers through an online response evaluation and optimization process, eliminating the necessity for offline training. This directly addresses one of the research problems.

5.2 Future Work

The purpose of this study was to provide structural vibration control systems to use with semi-active vibration control systems. Although the robustness of the developed algorithms was proved, their performance depends on other factors which need more investigation. The optimum number of dampers, the best dampers' locations, the performance of other types of Fuzzy Logic membership functions, and the application of the developed systems on a real prototype structural system are considered limitations of this research, as they are not included in the scope of work and therefore require future investigations.

The applicability of the developed FLMVOC and Online-FLMVOC needs to be investigated when other semi-active dampers are utilized, such as fluid viscous dampers.

Another proposed investigation is to enhance the system's ability to withstand uncertainties in external loads during the offline training by applying synthesis excitations and then utilizing the Pareto Optimal Controller in the FIS Memory.

Studying the performance of the developed vibration control systems after determining the optimal distribution of the dampers also need to be investigated.

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APPENDICES

Appendix A: Programming Codes for Online-Flmvoc Algorithm for Earthquake Excited Structure

```
%
%
% Online FLMVO Algorithm
%
% Developed in MATLAB R2016b
% Developed By Wisam Safaa Abdulateef 04-02-2022
% PhD Candidate/Civil Engineering Dept/ Faculty of Engineering /Universiti
% Putra Malaysia. (2020-2023)
% All rights reserved
%

clear all;
close all;
clc;
%Declare Variables for simulation
global fControl;global fControlElc;global fControlN;
global maxD_elc;global maxD_North;global Des_acc;
global elcentro;global northridge;
global y_cont;global fControlopt; global fControloptN;
global y_contN;global y_contOPT;global y_contNOPT;
global force_i;global y_uncOPT;global y_uncNOPT;
global eq_northridge;global earthquake_k;
% design Acceleration
Des_acc=9.81;
%=====
%% Simulation for Structure
fControl=readfis('FISControl.fis');
fControlopt=readfis('FISControl.fis');
%-----
% Real Time Simulation for each 100 time step or 50 time step for more
% adaptivity
% open two workers of parallel computation, so the optimization and
% control action run simultaneously
load('optimum_pos_data_EQ&WIND.mat');% using any training data,sequent onlineFLMVO
%% Earthquakes Properties
elcentro =load('Elcentro.mat');
elcentro=transpose(elcentro.e);
northridge=load('northrdg.mat');northridge=transpose(northridge.n);
% Shear Structure
M = [98.3 0 0; 0 98.3 0; 0 0 98.3];
K = [12 -6.84 0; -6.84 13.7 -6.84; 0 -6.84 6.84]*1e5;
% find matrix C, using Rayleigh damping
% Chopra procedure shown in Section 11.4 Pag 459
% w1 = 7.414; %natural frequency 1
% w2 = 20.48; %natural frequency 2

% w3 = 30.42;

w=sort(sqrt(eig(M\K)));
w1=w(1);
w2=w(2);
```

```

w3=w(3);
%----- RAYLEIGH METHOD -----%
%Using 5% damping on the first 2 modes, solve for a0 and a1
syms aa0 aa1

W=[1/w1 w1; 1/w2 w2];
zeta = 2*[0.05;0.05];
[aa0,aa1]=solve(W*[aa0;aa1]==zeta);
aa0=sym2poly(aa0);
aa1=sym2poly(aa1);
C= aa0*M + aa1*K; % Damping Matrix
C=[175 -50 0;-50 100 -50;0 -50 50];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The commented code is kept intentionally for further researches
%B=[zeros(3,3);M'];

% This section is for structure with controller attached in 1st floor and for full
state observation
% -----
C_u=[-M\K -M\C ;eye(3,3) zeros(3,3);zeros(3) eye(3)]% N refer to Normal Variables
not Composite
D1=zeros(length(M));
D2=[-1 0 0;0 0 0;0 0 0];
D=[M\D2 zeros(3,3);zeros(6)];
A=[zeros(3,3) eye(3,3); -K/M -C/M];
B=[zeros(3,6) ; M\D2 -M\eye(3)];
B_u=-[zeros(3,3); -eye(3)/M];% uncontrolled structure-use only eye(3) instead of
eye(3)/M if you don't multiply excitatin by M
D_u=zeros(9,3);% for Uncontrolled
% Declare FIS Memory
memSize=10;% memory size
FISmemElc=100*ones(memSize,112);
FISmemNorth=100*ones(memSize,112);
% Assign initial Contrtrollers in FISmemory ; gotten from initial
% optimization for a specified problem
Rt='OnlineFLMVOEQ_random';% File of previous trained data
traFIElc=load(Rt,'FISmemElc');
traFINorth=load(Rt,'FISmemNorth');
FISmemElc(1:size(optimum_pos_data(:,1)),:)=traFIElc.FISmemElc(1:size
(optimum_pos_data(:,1)),:);% change to 'optimum_pos_data.mat' if off line
optimization data is used
FISmemNorth(1:size(optimum_pos_data(:,1)),:)=traFINorth.FISmemNorth(1:size
(optimum_pos_data(:,1)),:);
FISmemElc(memSize,:)=optimum_pos_data(3,:)% activate when pretrained data is used
FISmemNorth(memSize,:)=optimum_pos_data(3,:)%optimum FLC from initial optimization
%% Simulation
c=1;
m=0;
for S=1:50:800% don't forget to change the Period in Simulink to suitable value

    earthquake_kopt = timeseries(elcentro(S:50*c,2),elcentro(1:50,1))% el centro
earthquake
    eq_northridgeopt=timeseries(northridge(S:50*c,2),northridge(1:50,1));

```

```

earthquake_k = timeseries(elcentro(S:50*c,2),elcentro(1:50,1))% el centro
earthquake
eq_northridge=timeseries(northridge(S:50*c,2),northridge(1:50,1));
sim('uncontSTRSIMOPT.slx');
% Assign Optimum FIS in Each Direction
MDriftElc=max(abs(y_uncOPT(:,4)))% max drift in Y direction @ step C
MDriftN=max(abs(y_uncNOPT(:,4)));
MAccElc=max(abs(y_uncOPT(:,1)));
MAccN=max(abs(y_uncNOPT(:,1)));
maxD_elc=0.0054;MaxRElc=[MDriftElc,MAccElc];
maxD_North=0.0096;MaxRN=[MDriftN,MAccN];
% Initial parameters of the Optimization algorithm
max_iter=1;
N=5;
ArchiveMaxSize=50;
dim=110;
obj_no=2;

tic % record the time spent at each optimization cycle
%% Run the Optimization

%% ----- MOMVO -----

%% Search in space to get optimized value for FL
[Best_universe_scoreElc,Best_universe_posElc,Archive_FY]=MOMVO(max_iter,N,
ArchiveMaxSize,fControl);
[Best_universe_scoreN,Best_universe_posN,Archive_FX]=MOMVONorth(max_iter,N,
ArchiveMaxSize,fControl);
fprintf('Optimization is done for the load step %0.0f \n',c);
if toc>=1000
    % Simulation For FL Controller and MR Damper
    %% Assign Opt Controllers
    fControlElc=GetOpFIS(FISmemElc,MDriftElc,MAccElc,maxD_elc,Des_acc);
    fControlN=GetOpFIS(FISmemNorth,MDriftN,MAccN,maxD_North,Des_acc);
    sim('OnlineFLMVOSystem.slx')
    disp(['Control Action Number ',num2str(c),' is Completed'])
    %% FIS Memory Updating
    [~,I]=sort(FISmemElc(:,111)); % Sort Ascending
    FISmemElc=FISmemElc(I,:);
    [~,I]=sort(FISmemNorth(:,111));
    FISmemNorth=FISmemNorth(I,:);
    % for k=1:size(FISmemElc(:,1))
    if all(Best_universe_scoreElc<=FISmemElc(memSize,111:112)) && any
(Best_universe_scoreElc<FISmemElc(memSize,111:112))
        FISmemElc(memSize,:)=[Best_universe_posElc,Best_universe_scoreElc];
    end
    if all(Best_universe_scoreN<=FISmemNorth(memSize,111:112)) && any
(Best_universe_scoreN<FISmemNorth(memSize,111:112))
        FISmemNorth(memSize,:)=[Best_universe_posN,Best_universe_scoreN];
    end
else
    %% FIS Memory Updating
    [~,I]=sort(FISmemElc(:,111));

```

```

FISmemElc=FISmemElc(I,:);
[~,I]=sort(FISmemNorth(:,111));
FISmemNorth=FISmemNorth(I,:);
% for k=1:size(FISmemElc(:,1))
if all(Best_universe_scoreElc<=FISmemElc(memSize,111:112)) && any
(Best_universe_scoreElc<FISmemElc(memSize,111:112))
    FISmemElc(memSize,:)= [Best_universe_posElc,Best_universe_scoreElc];
end
if all(Best_universe_scoreN<=FISmemNorth(memSize,111:112)) && any
(Best_universe_scoreN<FISmemNorth(memSize,111:112))
    FISmemNorth(memSize,:)= [Best_universe_posN,Best_universe_scoreN];
end
% Simulation For FL Controller and MR Damper
%% Assign Opt Controllers
fControlElc=GetOpFIS(FISmemElc,MDriftElc,MAccElc,maxD_elc,Des_acc);
fControlN=GetOpFIS(FISmemNorth,MDriftN,MAccN,maxD_North,Des_acc);
sim('OnlineFLMVOSystem.slx')
disp(['Control Action Number ',num2str(c),' is Completed'])
end
% Save The controlled Response
R_TableElc(m*12000+1:12000*c,:)=y_cont(1:12000,:); % 12000 is the number of
Simulink outputs steps for 1.2 sec of period
R_TableElcUNC(m*12000+1:12000*c,:)=y_uncOPT(1:12000,:);
R_TableN(m*12000+1:12000*c,:)=y_contN(1:12000,:);
R_TableNUNC(m*12000+1:12000*c,:)=y_uncNOPT(1:12000,:);
V_TableElc(m*12000+1:12000*c,:)=V_elcentro(1:12000,:);
V_TableN(m*12000+1:12000*c,:)=V_Northridge(1:12000,:);
F_TableElc(m*12000+1:12000*c,:)=force_i(1:12000,:);
F_TableN(m*12000+1:12000*c,:)=force_i2(1:12000,:);
c=c+1;
m=m+1;
end
save('OnlineFLMVOEQ_pretrained.
mat','FISmemElc','FISmemNorth','R_TableElc','R_TableElcUNC','V_TableElc','F_TableElc',
c','R_TableN','R_TableNUNC','V_TableN','F_TableN');

```

Appendix B: Programming Codes for Online-Flmvoc Algorithm for Earthquake Excited Structure

```
%
%
% Online FLMVO Algorithm
%
% Developed in MATLAB R2016b
% Developed By Wisam Safaa Abdulateef 04-02-2022
% PhD Candidate/Civil Engineering Dept/ Faculty of Engineering /Universiti
% Putra Malaysia. (2020-2023)
% All rights reserved
%

clear all;
close all;
clc;
%Declare Variables for simulation
global fControl;global WindL;global NsFlag;global R_Table_Unc;
global FJ60YFL;global DYFL;global AYFL;global Vel_YFL;
global FJ60YFR;global DYFR;global AYFR;global Vel_YFR;
global FJ60YBL;global DYBR;global AYBL;global Vel_YBL;
global FJ60YBR;global DYBL;global AYBR;global Vel_YBR;
global FJ60XFL;global DXFL;global AXFL;global Vel_XFL;
global FJ60XFR;global DXFR;global AXFR;global Vel_XFR;
global FJ60XBL;global DXBL;global AXBL;global Vel_XBL;
global FJ60XBR;global DXBR;global AXBR;global Vel_XBR;
%
%Global Variables for Optimizatoin
global FYFL;
global FYFR;
global FYBL;
global FYBR;
global FXFL;
global FXFR;
global FXBL;
global FXBR;
%=====
global maxD_X;global maxD_Y;global Des_acc;
% Declare FIS Memory
memSize=10;% memory size
FISmem=1000*ones(memSize,112);
FISmemX=1000*ones(memSize,112);
% Assign initial Contrtrollers in FISmemory ; gotten from initial
% optimization for a specified problem
load('optimum_pos_data.mat');
FISmem(1:size(optimum_pos_data(:,1)),:)=optimum_pos_data;
FISmemX(1:size(optimum_pos_data(:,1)),:)=optimum_pos_data;

%% Simulation for Structure
%% set the path for the ETABS DLL file in the installation folder
APIDLLPath = 'C:\Program Files\Computers and Structures\ETABS 19\ETABSv1.dll';

%% create API helper object
```

```

a = NET.addAssembly(APIDLLPath);
helper = ETABSV1.Helper;
helper = NET.explicitCast(helper,'ETABSV1.cHelper');

ETABSOBJ = helper.GetObject('CSI.ETABS.API.ETABSOBJ');
ETABSOBJ = NET.explicitCast(ETABSOBJ,'ETABSV1.cOAPI');
%% create SapModel object
SapModel = NET.explicitCast(ETABSOBJ.SapModel,'ETABSV1.cSapModel');
% Set Present Units to N_m_C
ret = SapModel.SetPresentUnits(ETABSV1.eUnits.N_m_C);

%% assign load
% Get wind load Time History
WfPath='E:\HDD Content\PhD Study\Disseetation chapters and data\Useful Matla
Codes\Inuse\60StoryAnalysing\76StoryBuilding\WindL.mat';
WindL=load(WfPath);
%% Defining cycles for # steps
% initial values of control forces
fControl=readfis('fControlW0412.fis');% Initial FL Controller For Optimization
FJ60YFL=[0;0.0001];F73YR=[0;0.0001];F70YR=[0;0.0001];
FJ60YFR=[0;0.0001];F73YL=[0;0.0001];F70YL=[0;0.0001];
FJ60YBR=[0;0.0001];F73XF=[0;0.0001];F70XF=[0;0.0001];
FJ60YBL=[0;0.0001];F73XB=[0;0.0001];F70XB=[0;0.0001];
FJ60XFL=[0;0.0001];
FJ60XFR=[0;0.0001];
FJ60XBR=[0;0.0001];
FJ60XBL=[0;0.0001];
% Set Number of Controlled Storys Flag (1 for story 75 only)
NsFlag=1;
% Get Max Drift
load('E:\HDD Content\PhD Study\Disseetation chapters and data\Useful Matla
Codes\Inuse\60StoryAnalysing\76StoryBuilding\Results\uncontr75.mat') % Load
Uncontrol response
load('E:\HDD Content\PhD Study\Disseetation chapters and data\Useful Matla
Codes\Inuse\60StoryAnalysing\76StoryBuilding\Results\uncontr73.mat') % Load
Uncontrol response
load('E:\HDD Content\PhD Study\Disseetation chapters and data\Useful Matla
Codes\Inuse\60StoryAnalysing\76StoryBuilding\Results\uncontr70.mat') % Load
Uncontrol response
maxD_X=max(abs(R_Table_Unc.Drift_X)); % Max Uncontrolled Value
maxD_Y=max(abs(R_Table_Unc.Drift_Y));
%-----
maxD_X73=max(abs(R_Table_Unc73.Drift_X)); % Max Uncontrolled Value
maxD_Y73=max(abs(R_Table_Unc73.Drift_Y));
%-----
maxD_X70=max(abs(R_Table_Unc70.Drift_X)); % Max Uncontrolled Value
maxD_Y70=max(abs(R_Table_Unc70.Drift_Y));
% Design Acceleration
Des_acc=0.2; % 20 milli g
% Assign Loads
PointObj=NET.explicitCast(SapModel.PointObj,'ETABSV1.cPointObj');
THLoad=NET.explicitCast(SapModel.LoadCases,'ETABSV1.cLoadCases');
THLoad=NET.explicitCast(THLoad.DirHistLinear,'ETABSV1.cCaseDirectHistoryLinear');

```

```

%% Start Online-FLMVOC

for C=21:30
c=C-1;
    %% Set wind Load and control force for each step and Story

    ret=PointObj.SetLoadForce('J76','WX',[WindL.FXc(1,C),0,0,0,0,0],true);
    ret=PointObj.SetLoadForce('J76','WY',[0,WindL.FYc(1,C),0,0,0,0],true);
    % ret=PointObj.SetLoadForce('J76','Wxy',[0,0,0,0,0,WindL.Mxyc(1,C)],true);

    ret=PointObj.SetLoadForce('J75','WX',[WindL.FXc(2,C),0,0,0,0,0],true);
    ret=PointObj.SetLoadForce('J75','WY',[0,WindL.FYc(2,C),0,0,0,0],true);
    % ret=PointObj.SetLoadForce('J59','Wxy',[0,0,0,0,0,WindL.Mxyc(2,C)],true);

    ret=PointObj.SetLoadForce('J74','WX',[WindL.FXc(3,C),0,0,0,0,0],true);
    ret=PointObj.SetLoadForce('J74','WY',[0,WindL.FYc(3,C),0,0,0,0],true);
    % ret=PointObj.SetLoadForce('J58','Wxy',[0,0,0,0,0,WindL.Mxyc(3,C)],true);

    ret=PointObj.SetLoadForce('J73','WX',[WindL.FXc(4,C),0,0,0,0,0],true);
    ret=PointObj.SetLoadForce('J73','WY',[0,WindL.FYc(4,C),0,0,0,0],true);
    % ret=PointObj.SetLoadForce('J57','Wxy',[0,0,0,0,0,WindL.Mxyc(4,C)],true);

    ret=PointObj.SetLoadForce('J72','WX',[WindL.FXc(5,C),0,0,0,0,0],true);
    ret=PointObj.SetLoadForce('J72','WY',[0,WindL.FYc(5,C),0,0,0,0],true);
    % ret=PointObj.SetLoadForce('J56','Wxy',[0,0,0,0,0,WindL.Mxyc(5,C)],true);

    ret=PointObj.SetLoadForce('J71','WX',[WindL.FXc(6,C),0,0,0,0,0],true);
    ret=PointObj.SetLoadForce('J71','WY',[0,WindL.FYc(6,C),0,0,0,0],true);
    % ret=PointObj.SetLoadForce('J55','Wxy',[0,0,0,0,0,WindL.Mxyc(6,C)],true);

    ret=PointObj.SetLoadForce('J70','WX',[WindL.FXc(7,C),0,0,0,0,0],true);
    ret=PointObj.SetLoadForce('J70','WY',[0,WindL.FYc(7,C),0,0,0,0],true);
    % ret=PointObj.SetLoadForce('J54','Wxy',[0,0,0,0,0,WindL.Mxyc(7,C)],true);

    ret=PointObj.SetLoadForce('J69','WX',[WindL.FXc(8,C),0,0,0,0,0],true);
    ret=PointObj.SetLoadForce('J69','WY',[0,WindL.FYc(8,C),0,0,0,0],true);
    % ret=PointObj.SetLoadForce('J53','Wxy',[0,0,0,0,0,WindL.Mxyc(8,C)],true);

    ret=PointObj.SetLoadForce('J68','WX',[WindL.FXc(9,C),0,0,0,0,0],true);
    ret=PointObj.SetLoadForce('J68','WY',[0,WindL.FYc(9,C),0,0,0,0],true);
    % ret=PointObj.SetLoadForce('J52','Wxy',[0,0,0,0,0,WindL.Mxyc(9,C)],true);

    ret=PointObj.SetLoadForce('J67','WX',[WindL.FXc(10,C),0,0,0,0,0],true);
    ret=PointObj.SetLoadForce('J67','WY',[0,WindL.FYc(10,C),0,0,0,0],true);
    % ret=PointObj.SetLoadForce('J51','Wxy',[0,0,0,0,0,WindL.Mxyc(10,C)],true);

    ret=PointObj.SetLoadForce('J66','WX',[WindL.FXc(11,C),0,0,0,0,0],true);
    ret=PointObj.SetLoadForce('J66','WY',[0,WindL.FYc(11,C),0,0,0,0],true);
    % ret=PointObj.SetLoadForce('J50','Wxy',[0,0,0,0,0,WindL.Mxyc(11,C)],true);

    ret=PointObj.SetLoadForce('J65','WX',[WindL.FXc(12,C),0,0,0,0,0],true);
    ret=PointObj.SetLoadForce('J65','WY',[0,WindL.FYc(12,C),0,0,0,0],true);
    % ret=PointObj.SetLoadForce('J49','Wxy',[0,0,0,0,0,WindL.Mxyc(12,C)],true);

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```

ret=PointObj.SetLoadForce('J64','WX',[WindL.FXc(13,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J64','WY',[0,WindL.FYc(13,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J48','Wxy',[0,0,0,0,0,WindL.Mxyc(13,C)],true);

ret=PointObj.SetLoadForce('J63','WX',[WindL.FXc(14,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J63','WY',[0,WindL.FYc(14,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J47','Wxy',[0,0,0,0,0,WindL.Mxyc(14,C)],true);

ret=PointObj.SetLoadForce('J62','WX',[WindL.FXc(15,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J62','WY',[0,WindL.FYc(15,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J46','Wxy',[0,0,0,0,0,WindL.Mxyc(15,C)],true);

ret=PointObj.SetLoadForce('J61','WX',[WindL.FXc(16,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J61','WY',[0,WindL.FYc(16,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J45','Wxy',[0,0,0,0,0,WindL.Mxyc(16,C)],true);

ret=PointObj.SetLoadForce('J60','WX',[WindL.FXc(17,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J60','WY',[0,WindL.FYc(17,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J44','Wxy',[0,0,0,0,0,WindL.Mxyc(17,C)],true);

ret=PointObj.SetLoadForce('J59','WX',[WindL.FXc(18,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J59','WY',[0,WindL.FYc(18,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J43','Wxy',[0,0,0,0,0,WindL.Mxyc(18,C)],true);

ret=PointObj.SetLoadForce('J58','WX',[WindL.FXc(19,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J58','WY',[0,WindL.FYc(19,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J42','Wxy',[0,0,0,0,0,WindL.Mxyc(19,C)],true);

ret=PointObj.SetLoadForce('J57','WX',[WindL.FXc(20,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J57','WY',[0,WindL.FYc(20,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J41','Wxy',[0,0,0,0,0,WindL.Mxyc(20,C)],true);

ret=PointObj.SetLoadForce('J56','WX',[WindL.FXc(21,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J56','WY',[0,WindL.FYc(21,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J40','Wxy',[0,0,0,0,0,WindL.Mxyc(21,C)],true);

ret=PointObj.SetLoadForce('J55','WX',[WindL.FXc(22,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J55','WY',[0,WindL.FYc(22,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J39','Wxy',[0,0,0,0,0,WindL.Mxyc(22,C)],true);

ret=PointObj.SetLoadForce('J54','WX',[WindL.FXc(23,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J54','WY',[0,WindL.FYc(23,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J38','Wxy',[0,0,0,0,0,WindL.Mxyc(23,C)],true);

ret=PointObj.SetLoadForce('J53','WX',[WindL.FXc(24,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J53','WY',[0,WindL.FYc(24,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J37','Wxy',[0,0,0,0,0,WindL.Mxyc(24,C)],true);

ret=PointObj.SetLoadForce('J52','WX',[WindL.FXc(25,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J52','WY',[0,WindL.FYc(25,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J36','Wxy',[0,0,0,0,0,WindL.Mxyc(25,C)],true);

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```

ret=PointObj.SetLoadForce('J51','WX',[WindL.FXc(26,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J51','WY',[0,WindL.FYc(26,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J35','Wxy',[0,0,0,0,0,WindL.Mxyc(26,C)],true);

ret=PointObj.SetLoadForce('J50','WX',[WindL.FXc(27,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J50','WY',[0,WindL.FYc(27,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J34','Wxy',[0,0,0,0,0,WindL.Mxyc(27,C)],true);

ret=PointObj.SetLoadForce('J49','WX',[WindL.FXc(28,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J49','WY',[0,WindL.FYc(28,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J33','Wxy',[0,0,0,0,0,WindL.Mxyc(28,C)],true);

ret=PointObj.SetLoadForce('J48','WX',[WindL.FXc(29,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J48','WY',[0,WindL.FYc(29,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J32','Wxy',[0,0,0,0,0,WindL.Mxyc(29,C)],true);

ret=PointObj.SetLoadForce('J47','WX',[WindL.FXc(30,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J47','WY',[0,WindL.FYc(30,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J31','Wxy',[0,0,0,0,0,WindL.Mxyc(30,C)],true);

ret=PointObj.SetLoadForce('J46','WX',[WindL.FXc(31,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J46','WY',[0,WindL.FYc(31,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J30','Wxy',[0,0,0,0,0,WindL.Mxyc(31,C)],true);

ret=PointObj.SetLoadForce('J45','WX',[WindL.FXc(32,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J45','WY',[0,WindL.FYc(32,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J29','Wxy',[0,0,0,0,0,WindL.Mxyc(32,C)],true);

ret=PointObj.SetLoadForce('J44','WX',[WindL.FXc(33,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J44','WY',[0,WindL.FYc(33,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J28','Wxy',[0,0,0,0,0,WindL.Mxyc(33,C)],true);

ret=PointObj.SetLoadForce('J43','WX',[WindL.FXc(34,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J43','WY',[0,WindL.FYc(34,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J27','Wxy',[0,0,0,0,0,WindL.Mxyc(34,C)],true);

ret=PointObj.SetLoadForce('J42','WX',[WindL.FXc(35,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J42','WY',[0,WindL.FYc(35,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J26','Wxy',[0,0,0,0,0,WindL.Mxyc(35,C)],true);

ret=PointObj.SetLoadForce('J41','WX',[WindL.FXc(36,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J41','WY',[0,WindL.FYc(36,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J25','Wxy',[0,0,0,0,0,WindL.Mxyc(36,C)],true);

ret=PointObj.SetLoadForce('J40','WX',[WindL.FXc(37,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J40','WY',[0,WindL.FYc(37,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J24','Wxy',[0,0,0,0,0,WindL.Mxyc(37,C)],true);

ret=PointObj.SetLoadForce('J39','WX',[WindL.FXc(38,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J39','WY',[0,WindL.FYc(38,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J23','Wxy',[0,0,0,0,0,WindL.Mxyc(38,C)],true);

ret=PointObj.SetLoadForce('J38','WX',[WindL.FXc(39,C),0,0,0,0,0],true);

```

```

ret=PointObj.SetLoadForce('J38','WY',[0,WindL.FYc(39,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J22','Wxy',[0,0,0,0,0,WindL.Mxyc(39,C)],true);

ret=PointObj.SetLoadForce('J37','WX',[WindL.FXc(40,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J37','WY',[0,WindL.FYc(40,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J21','Wxy',[0,0,0,0,0,WindL.Mxyc(40,C)],true);

ret=PointObj.SetLoadForce('J36','WX',[WindL.FXc(42,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J36','WY',[0,WindL.FYc(42,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J20','Wxy',[0,0,0,0,0,WindL.Mxyc(42,C)],true);

ret=PointObj.SetLoadForce('J35','WX',[WindL.FXc(43,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J35','WY',[0,WindL.FYc(43,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J19','Wxy',[0,0,0,0,0,WindL.Mxyc(43,C)],true);

ret=PointObj.SetLoadForce('J34','WX',[WindL.FXc(44,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J34','WY',[0,WindL.FYc(44,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J18','Wxy',[0,0,0,0,0,WindL.Mxyc(44,C)],true);

ret=PointObj.SetLoadForce('J33','WX',[WindL.FXc(45,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J33','WY',[0,WindL.FYc(45,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J17','Wxy',[0,0,0,0,0,WindL.Mxyc(45,C)],true);

ret=PointObj.SetLoadForce('J32','WX',[WindL.FXc(46,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J32','WY',[0,WindL.FYc(46,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J16','Wxy',[0,0,0,0,0,WindL.Mxyc(46,C)],true);

ret=PointObj.SetLoadForce('J31','WX',[WindL.FXc(47,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J31','WY',[0,WindL.FYc(47,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J15','Wxy',[0,0,0,0,0,WindL.Mxyc(47,C)],true);

ret=PointObj.SetLoadForce('J30','WX',[WindL.FXc(48,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J30','WY',[0,WindL.FYc(48,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J14','Wxy',[0,0,0,0,0,WindL.Mxyc(48,C)],true);

ret=PointObj.SetLoadForce('J29','WX',[WindL.FXc(49,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J29','WY',[0,WindL.FYc(49,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J13','Wxy',[0,0,0,0,0,WindL.Mxyc(49,C)],true);

ret=PointObj.SetLoadForce('J28','WX',[WindL.FXc(50,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J28','WY',[0,WindL.FYc(50,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J12','Wxy',[0,0,0,0,0,WindL.Mxyc(50,C)],true);

ret=PointObj.SetLoadForce('J27','WX',[WindL.FXc(51,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J27','WY',[0,WindL.FYc(51,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J11','Wxy',[0,0,0,0,0,WindL.Mxyc(51,C)],true);

ret=PointObj.SetLoadForce('J26','WX',[WindL.FXc(52,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J26','WY',[0,WindL.FYc(52,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J10','Wxy',[0,0,0,0,0,WindL.Mxyc(52,C)],true);

ret=PointObj.SetLoadForce('J25','WX',[WindL.FXc(53,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J25','WY',[0,WindL.FYc(53,C),0,0,0,0],true);

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% ret=PointObj.SetLoadForce('J9','Wxy',[0,0,0,0,0,WindL.Mxyc(53,C)],true);

ret=PointObj.SetLoadForce('J24','WX',[WindL.FXc(54,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J24','WY',[0,WindL.FYc(54,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J8','Wxy',[0,0,0,0,0,WindL.Mxyc(54,C)],true);

ret=PointObj.SetLoadForce('J23','WX',[WindL.FXc(55,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J23','WY',[0,WindL.FYc(55,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J7','Wxy',[0,0,0,0,0,WindL.Mxyc(55,C)],true);

ret=PointObj.SetLoadForce('J22','WX',[WindL.FXc(56,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J22','WY',[0,WindL.FYc(56,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J6','Wxy',[0,0,0,0,0,WindL.Mxyc(56,C)],true);

ret=PointObj.SetLoadForce('J21','WX',[WindL.FXc(57,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J21','WY',[0,WindL.FYc(57,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J5','Wxy',[0,0,0,0,0,WindL.Mxyc(57,C)],true);

ret=PointObj.SetLoadForce('J20','WX',[WindL.FXc(58,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J20','WY',[0,WindL.FYc(58,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J4','Wxy',[0,0,0,0,0,WindL.Mxyc(58,C)],true);

ret=PointObj.SetLoadForce('J19','WX',[WindL.FXc(59,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J19','WY',[0,WindL.FYc(59,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J3','Wxy',[0,0,0,0,0,WindL.Mxyc(59,C)],true);

ret=PointObj.SetLoadForce('J18','WX',[WindL.FXc(60,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J18','WY',[0,WindL.FYc(60,C),0,0,0,0],true);
% ret=PointObj.SetLoadForce('J2','Wxy',[0,0,0,0,0,WindL.Mxyc(60,C)],true);

ret=PointObj.SetLoadForce('J17','WX',[WindL.FXc(60,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J17','WY',[0,WindL.FYc(60,C),0,0,0,0],true);

ret=PointObj.SetLoadForce('J16','WX',[WindL.FXc(61,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J16','WY',[0,WindL.FYc(61,C),0,0,0,0],true);

ret=PointObj.SetLoadForce('J15','WX',[WindL.FXc(62,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J15','WY',[0,WindL.FYc(62,C),0,0,0,0],true);

ret=PointObj.SetLoadForce('J14','WX',[WindL.FXc(63,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J14','WY',[0,WindL.FYc(63,C),0,0,0,0],true);

ret=PointObj.SetLoadForce('J13','WX',[WindL.FXc(64,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J13','WY',[0,WindL.FYc(64,C),0,0,0,0],true);

ret=PointObj.SetLoadForce('J12','WX',[WindL.FXc(65,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J12','WY',[0,WindL.FYc(65,C),0,0,0,0],true);

ret=PointObj.SetLoadForce('J11','WX',[WindL.FXc(66,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J11','WY',[0,WindL.FYc(66,C),0,0,0,0],true);

ret=PointObj.SetLoadForce('J10','WX',[WindL.FXc(67,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J10','WY',[0,WindL.FYc(67,C),0,0,0,0],true);

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ret=PointObj.SetLoadForce('J9','WX',[WindL.FXc(68,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J9','WY',[0,WindL.FYc(68,C),0,0,0,0],true);

ret=PointObj.SetLoadForce('J8','WX',[WindL.FXc(69,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J8','WY',[0,WindL.FYc(69,C),0,0,0,0],true);

ret=PointObj.SetLoadForce('J7','WX',[WindL.FXc(70,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J7','WY',[0,WindL.FYc(70,C),0,0,0,0],true);

ret=PointObj.SetLoadForce('J6','WX',[WindL.FXc(71,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J6','WY',[0,WindL.FYc(71,C),0,0,0,0],true);

ret=PointObj.SetLoadForce('J5','WX',[WindL.FXc(72,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J5','WY',[0,WindL.FYc(72,C),0,0,0,0],true);

ret=PointObj.SetLoadForce('J4','WX',[WindL.FXc(73,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J4','WY',[0,WindL.FYc(73,C),0,0,0,0],true);

ret=PointObj.SetLoadForce('J3','WX',[WindL.FXc(74,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J3','WY',[0,WindL.FYc(74,C),0,0,0,0],true);

ret=PointObj.SetLoadForce('J2','WX',[WindL.FXc(75,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J2','WY',[0,WindL.FYc(75,C),0,0,0,0],true);

ret=PointObj.SetLoadForce('J1','WX',[WindL.FXc(76,C),0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J1','WY',[0,WindL.FYc(76,C),0,0,0,0],true);

% ret=PointObj.SetLoadForce('J00','WX',[WindL.FXc(77,C),0,0,0,0,0],true);
% ret=PointObj.SetLoadForce('J00','WY',[0,WindL.FYc(77,C),0,0,0,0],true);

%% Assign Control Forces at Control Joints:
% get the action direction (sign of max force)
signYFL=sign(FJ60YFL); [FJ60YFL,I]=max(abs(FJ60YFL)); FJ60YFL=FJ60YFL*signYFL(I);
signYFR=sign(FJ60YFR); [FJ60YFR,I]=max(abs(FJ60YFR)); FJ60YFR=FJ60YFR*signYFR(I);
signYBL=sign(FJ60YBL); [FJ60YBL,I]=max(abs(FJ60YBL)); FJ60YBL=FJ60YBL*signYBL(I);
signYBR=sign(FJ60YBR); [FJ60YBR,I]=max(abs(FJ60YBR)); FJ60YBR=FJ60YBR*signYBR(I);
signXFL=sign(FJ60XFL); [FJ60XFL,I]=max(abs(FJ60XFL)); FJ60XFL=FJ60XFL*signXFL(I);
signXFR=sign(FJ60XFR); [FJ60XFR,I]=max(abs(FJ60XFR)); FJ60XFR=FJ60XFR*signXFR(I);
signXBL=sign(FJ60XBL); [FJ60XBL,I]=max(abs(FJ60XBL)); FJ60XBL=FJ60XBL*signXBL(I);
signXBR=sign(FJ60XBR); [FJ60XBR,I]=max(abs(FJ60XBR)); FJ60XBR=FJ60XBR*signXBR(I);
F_Table(C,:)= [FJ60YFL,FJ60YFR,FJ60YBL,FJ60YBR,FJ60XFL,FJ60XFR,FJ60XBL,FJ60XBR]';
Table Of Control Forces at involved iter.
ret=PointObj.SetLoadForce('J75YFL','FcY',[0,-FJ60YFL,0,0,0,0],true); % minus sign is
to simulate control force in the correct Direction
ret=PointObj.SetLoadForce('J75YFR','FcY',[0,-FJ60YFR,0,0,0,0],true);
ret=PointObj.SetLoadForce('J75YBL','FcY',[0,-FJ60YBL,0,0,0,0],true);
ret=PointObj.SetLoadForce('J75YBR','FcY',[0,-FJ60YBR,0,0,0,0],true);
ret=PointObj.SetLoadForce('J75XBL','FcX',[-FJ60XBL,0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J75XBR','FcX',[-FJ60XBR,0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J75XFL','FcX',[-FJ60XFL,0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J75XFR','FcX',[-FJ60XFR,0,0,0,0,0],true);

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%-----%
% Story 73
signYFL=sign(F73YL); [F73YL,I]=max(abs(F73YL)); F73YL=F73YL*signYFL(I);
signYFR=sign(F73YR); [F73YR,I]=max(abs(F73YR)); F73YR=F73YR*signYFR(I);
signYBL=sign(F73YL); [F73YL,I]=max(abs(F73YL)); F73YL=F73YL*signYBL(I);
signYBR=sign(F73YR); [F73YR,I]=max(abs(F73YR)); F73YR=F73YR*signYBR(I);
signXFL=sign(F73XF); [F73XF,I]=max(abs(F73XF)); F73XF=F73XF*signXFL(I);
signXFR=sign(F73XF); [F73XF,I]=max(abs(F73XF)); F73XF=F73XF*signXFR(I);
signXBL=sign(F73XB); [F73XB,I]=max(abs(F73XB)); F73XB=F73XB*signXBL(I);
signXBR=sign(F73XB); [F73XB,I]=max(abs(F73XB)); F73XB=F73XB*signXBR(I);
F_Table73(C,:)= [F73YL,F73YR,F73YL,F73YR,F73XF,F73XF,F73XB,F73XB] % Table Of Control
Forces at involved iter.
ret=PointObj.SetLoadForce('J73YFL','FcY',[0,-F73YL,0,0,0,0],true); % minus sign is
to simulate control force in the right Direction
% ret=PointObj.SetLoadForce('J73YFL1','FcY',[0,-F73YL,0,0,0,0],true);
ret=PointObj.SetLoadForce('J73YFR','FcY',[0,-F73YR,0,0,0,0],true);
% ret=PointObj.SetLoadForce('J73YFR1','FcY',[0,-F73YR,0,0,0,0],true);
ret=PointObj.SetLoadForce('J73YBL','FcY',[0,-F73YL,0,0,0,0],true);
% ret=PointObj.SetLoadForce('J73YBL1','FcY',[0,-F73YL,0,0,0,0],true);
ret=PointObj.SetLoadForce('J73YBR','FcY',[0,-F73YR,0,0,0,0],true);
% ret=PointObj.SetLoadForce('J73YBR1','FcY',[0,-F73YR,0,0,0,0],true);
ret=PointObj.SetLoadForce('J73XBL','FcX',[-F73XB,0,0,0,0,0],true);
% ret=PointObj.SetLoadForce('J73XBL1','FcX',[-F73XB,0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J73XBR','FcX',[-F73XB,0,0,0,0,0],true);
% ret=PointObj.SetLoadForce('J73XBR1','FcX',[-F73XB,0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J73XFL','FcX',[-F73XF,0,0,0,0,0],true);
% ret=PointObj.SetLoadForce('J73XFL1','FcX',[-F73XF,0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J73XFR','FcX',[-F73XF,0,0,0,0,0],true);
% ret=PointObj.SetLoadForce('J73XFR1','FcX',[-F73XF,0,0,0,0,0],true);
%-----%

% Story 70
signYFL=sign(F70YL); [F70YL,I]=max(abs(F70YL)); F70YL=F70YL*signYFL(I);
signYFR=sign(F70YR); [F70YR,I]=max(abs(F70YR)); F70YR=F70YR*signYFR(I);
signYBL=sign(F70YL); [F70YL,I]=max(abs(F70YL)); F70YL=F70YL*signYBL(I);
signYBR=sign(F70YR); [F70YR,I]=max(abs(F70YR)); F70YR=F70YR*signYBR(I);
signXFL=sign(F70XF); [F70XF,I]=max(abs(F70XF)); F70XF=F70XF*signXFL(I);
signXFR=sign(F70XF); [F70XF,I]=max(abs(F70XF)); F70XF=F70XF*signXFR(I);
signXBL=sign(F70XB); [F70XB,I]=max(abs(F70XB)); F70XB=F70XB*signXBL(I);
signXBR=sign(F70XB); [F70XB,I]=max(abs(F70XB)); F70XB=F70XB*signXBR(I);
F_Table70(C,:)= [F70YL,F70YR,F70YL,F70YR,F70XF,F70XF,F70XB,F70XB] % Table Of Control
Forces at involved iter.
ret=PointObj.SetLoadForce('J70YFL','FcY',[0,-F70YL,0,0,0,0],true); % minus sign is
to simulate control force in the right Direction
ret=PointObj.SetLoadForce('J70YFR','FcY',[0,-F70YR,0,0,0,0],true);
ret=PointObj.SetLoadForce('J70YBL','FcY',[0,-F70YL,0,0,0,0],true);
ret=PointObj.SetLoadForce('J70YBR','FcY',[0,-F70YR,0,0,0,0],true);
ret=PointObj.SetLoadForce('J70XBL','FcX',[-F70XB,0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J70XBR','FcX',[-F70XB,0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J70XFL','FcX',[-F70XF,0,0,0,0,0],true);
ret=PointObj.SetLoadForce('J70XFR','FcX',[-F70XF,0,0,0,0,0],true);
%=====

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%% Get The response From ETABS
% run model (this will create the analysis model)
Analyze = NET.explicitCast(SapModel.Analyze,'ETABSv1.cAnalyze');
ret = Analyze.RunAnalysis();
NumberResults = 0;

%% Define Acceleration Method Parameters
LoadCase=NET.createArray('System.String',1);
Obj=NET.createArray('System.String',1);
Elm=NET.createArray('System.String',1);
StepType=NET.createArray('System.String',1);
StepNum =NET.createArray('System.Double',20);
U1=NET.createArray('System.Double',1);
U2=NET.createArray('System.Double',1);
U3=NET.createArray('System.Double',1);
R1=NET.createArray('System.Double',1);
R2=NET.createArray('System.Double',1);
R3=NET.createArray('System.Double',1);
%% Define Displacement Method Parameters
NumberResultst = 0;
LoadCaset=NET.createArray('System.String',1);
Objt=NET.createArray('System.String',1);
Elmt=NET.createArray('System.String',1);
StepTypet=NET.createArray('System.String',1);
StepNumt =NET.createArray('System.Double',20);
U1t=NET.createArray('System.Double',1);
U2t=NET.createArray('System.Double',1);
U3t=NET.createArray('System.Double',1);
R1t=NET.createArray('System.Double',1);
R2t=NET.createArray('System.Double',1);
R3t=NET.createArray('System.Double',1);

%% Define Velocity Method Parameters
LoadCase1=NET.createArray('System.String',1);
Obj1=NET.createArray('System.String',1);
Elm1=NET.createArray('System.String',1);
StepType1=NET.createArray('System.String',1);
StepNum1 =NET.createArray('System.Double',20);
U1v=NET.createArray('System.Double',1);
U2v=NET.createArray('System.Double',1);
U3v=NET.createArray('System.Double',1);
R1v=NET.createArray('System.Double',1);
R2v=NET.createArray('System.Double',1);
R3v=NET.createArray('System.Double',1);
NumberResultsv = 0;
% Define Drift Method Parameters
NumberResultsD = 0;
Story = NET.createArray('System.String',60);
LCase = NET.createArray('System.String',1);
Name = NET.createArray('System.String',1);
StepnumD=NET.createArray('System.Double',60);
StepTypeD = NET.createArray('System.String',6);
DX = NET.createArray('System.Double',60);
Label = NET.createArray('System.String',60);

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X = NET.createArray('System.Double',60);
Y = NET.createArray('System.Double',60);
DY = NET.createArray('System.Double',60);
%% get ETABS results for load case WindL
AnalysisResults = NET.explicitCast(SapModel.Results,ETABSV1.cAnalysisResults);
AnalysisResultsSetup = NET.explicitCast(AnalysisResults.Setup,ETABSV1.cAnalysisResultsSetup);
ret = AnalysisResultsSetup.DeselectAllCasesAndCombosForOutput;
ret = AnalysisResultsSetup.SetOptionModalHist(1);
ret = AnalysisResultsSetup.SetCaseSelectedForOutput(WindL,true);
[dis,NumberResultst,Objt, Elmt,LoadCaset, StepTypet, StepNumt, U1t, U2t, U3t, R1t, R2t, R3t]=AnalysisResults.JointDisplAbs('J75G',ETABSV1.eItemTypeElm.GroupElm,NumberResultst,Objt, Elmt,LoadCaset, StepTypet, StepNumt, U1t, U2t, U3t, R1t, R2t, R3t);
[ACC,NumberResults,Obj, Elm,LoadCase, StepType, StepNum, U1, U2, U3, R1, R2, R3]=AnalysisResults.JointAccAbs('J75G',ETABSV1.eItemTypeElm.GroupElm,NumberResults,Obj, Elm,LoadCase, StepType, StepNum, U1, U2, U3, R1, R2, R3);
[Vel,NumberResultsv,Obj1, Elmt,LoadCase1, StepType1, StepNum1, U1v, U2v, U3v, R1v, R2v, R3v]=AnalysisResults.JointVelAbs('J75G',ETABSV1.eItemTypeElm.GroupElm,NumberResultsv,Obj1, Elmt,LoadCase1, StepType1, StepNum1, U1v, U2v, U3v, R1v, R2v, R3v);
ret=PointObj.SetSelected('J75G',true,ETABSV1.eItemType.Group);
[ret,N,Story, Label, Name, LCase, StepTypeD, StepnumD, X, Y, DriftX, DriftY] = AnalysisResults.JointDrifts(NumberResultsD,Story, Label, Name, LCase, StepTypeD, StepnumD, X, Y, DX, DY);

% retrieve Displacement values Story 75
TableDis=GetDisp( NumberResultst,LoadCaset,StepTypet,Objt,U1t,U2t,R3t);
% retrieve Acceleration Values# Story75
TableACC=GetAcc( NumberResults,LoadCase,StepNum,Obj,U1,U2,R3);
% Get Drifts results#Story 75
JLabel=
{'11','16','21','26','41','46','51','56','166','171','176','181','186','191','196','201'};
DriftTable=GetDrift('Story75',N,JLabel,Story,LCase,StepTypeD,StepnumD,DriftX,DriftY,Label);
% retrieve Velocity Values #Story 75
TableVel=GetVel( NumberResultsv,LoadCase1,StepNum1,Obj1,U1v,U2v,R3v );

%% Story 73 & Story 70
if NsFlag>1

[dis,NumberResultst,Objt, Elmt,LoadCaset, StepTypet, StepNumt, U1t, U2t, U3t, R1t, R2t, R3t]=AnalysisResults.JointDisplAbs('J73G',ETABSV1.eItemTypeElm.GroupElm,NumberResultst,Objt, Elmt,LoadCaset, StepTypet, StepNumt, U1t, U2t, U3t, R1t, R2t, R3t);
[ACC,NumberResults,Obj, Elm,LoadCase, StepType, StepNum, U1, U2, U3, R1, R2, R3]=AnalysisResults.JointAccAbs('J73G',ETABSV1.eItemTypeElm.GroupElm,NumberResults,Obj, Elm,LoadCase, StepType, StepNum, U1, U2, U3, R1, R2, R3);
[Vel,NumberResultsv,Obj1, Elmt,LoadCase1, StepType1, StepNum1, U1v, U2v, U3v, R1v, R2v, R3v]=AnalysisResults.JointVelAbs('J73G',ETABSV1.eItemTypeElm.GroupElm,NumberResultsv,Obj1, Elmt,LoadCase1, StepType1, StepNum1, U1v, U2v, U3v, R1v, R2v, R3v);

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ret=PointObj.SetSelected('J73G',true,ETABSv1.eItemType.Group);
[ret,N,Story, Label, Name, LCase, StepTypeD, StepnumD, X, Y, DriftX, DriftY] =
AnalysisResults.JointDrifts(NumberResultsD,Story, Label, Name, LCase, StepTypeD,
StepnumD, X, Y, DX, DY);

% retrieve Displacement values Story 73
TableDis73=GetDisp( NumberResultst,LoadCaset,StepTypet,Objt,U1t,U2t,R3t);
% retrieve Acceleration Values# Story73
TableACC73=GetAcc( NumberResults,LoadCase,StepNum,Obj,U1,U2,R3);
% Get Drifts results#Story 73
JLabel=
{'11','16','21','26','41','46','51','56','166','171','176','181','186','191','196','
'201'};
DriftTable73=GetDrift('Story73',N,JLabel,Story,LCase,StepTypeD,StepnumD,DriftX,
DriftY,Label);
% retrieve Velocity Values #Story 73
TableVel73=GetVel( NumberResultsv,LoadCase1,StepNum1,Obj1,U1v,U2v,R3v );
%% Story 70
[dis,NumberResultst,Objt, Elmt,LoadCaset, StepTypet, StepNumt, U1t, U2t, U3t, R1t,
R2t, R3t]=AnalysisResults.JointDisplAbs('J70G',ETABSv1.eItemTypeElm.GroupElm,
NumberResultst,Objt, Elmt,LoadCaset, StepTypet, StepNumt, U1t, U2t, U3t, R1t, R2t,
R3t);
[ACC,NumberResults,Obj, Elm,LoadCase, StepType, StepNum, U1, U2, U3, R1, R2, R3]
=AnalysisResults.JointAccAbs('J70G',ETABSv1.eItemTypeElm.GroupElm,NumberResults,
Obj, Elm,LoadCase, StepType, StepNum, U1, U2, U3, R1, R2, R3);
[Vel,NumberResultsv,Obj1, Elm1,LoadCase1, StepType1, StepNum1, U1v, U2v, U3v, R1v,
R2v, R3v]=AnalysisResults.JointVelAbs('J70G',ETABSv1.eItemTypeElm.GroupElm,
NumberResultsv,Obj1, Elm1,LoadCase1, StepType1, StepNum1, U1v, U2v, U3v, R1v, R2v,
R3v);
ret=PointObj.SetSelected('J70G',true,ETABSv1.eItemType.Group);
[ret,N,Story, Label, Name, LCase, StepTypeD, StepnumD, X, Y, DriftX, DriftY] =
AnalysisResults.JointDrifts(NumberResultsD,Story, Label, Name, LCase, StepTypeD,
StepnumD, X, Y, DX, DY);

% retrieve Displacement values Story 70
TableDis70=GetDisp( NumberResultst,LoadCaset,StepTypet,Objt,U1t,U2t,R3t);
% retrieve Acceleration Values# Story70
TableACC70=GetAcc( NumberResults,LoadCase,StepNum,Obj,U1,U2,R3);
% Get Drifts results#Story 70
JLabel=
{'11','16','21','26','41','46','51','56','166','171','176','181','186','191','196','
'201'};
DriftTable70=GetDrift('Story70',N,JLabel,Story,LCase,StepTypeD,StepnumD,DriftX,
DriftY,Label);
% retrieve Velocity Values #Story 70
TableVel70=GetVel( NumberResultsv,LoadCase1,StepNum1,Obj1,U1v,U2v,R3v );
end
%% Unlock Model
ret = SapModel.SetModelIsLocked(false);

%% Define Parameters for Simulink
T=0.0001;
% Story 75

```

```

% 1-Drifts
% Regulation for Instability probability
if max(abs(DriftTable.Drift_Y)) > (max(abs(R_Table_Unc.Drift_Y(c*32+1:32*C))))
    DYFL=0;
    DYBL=0;
    DYFR=0;
    DYBR=0;
else
    DYFL=max(abs(DriftTable.Drift_Y(13:14)));
    DYBL=max(abs(DriftTable.Drift_Y(9:10)));
    DYFR=max(abs(DriftTable.Drift_Y(29:30)));
    DYBR=max(abs(DriftTable.Drift_Y(25:26)));
end
if max(abs(DriftTable.Drift_X)) > (max(abs(R_Table_Unc.Drift_X(c*32+1:32*C))))
    DXFL=0;
    DXBL=0;
    DXFR=0;
    DXBR=0;
else
    DXFL=max(abs(DriftTable.Drift_X(19:20)));
    DXBL=max(abs(DriftTable.Drift_X(3:4)));
    DXFR=max(abs(DriftTable.Drift_X(23:24)));
    DXBR=max(abs(DriftTable.Drift_X(7:8)));
end

DYFL=timeseries(DYFL,T);
DYBL=timeseries(DYBL,T);
DYFR=timeseries(DYFR,T);
DYBR=timeseries(DYBR,T);
DXFL=timeseries(DXFL,T);
DXBL=timeseries(DXBL,T);
DXFR=timeseries(DXFR,T);
DXBR=timeseries(DXBR,T);

% 2- Accelerations
% Regulation for Instability probability
if max(abs(TableACC.AccY)) > (max(abs(R_Table_Unc.AccY(c*32+1:32*C))))
    AYFL=0;
    AYFR=0;
    AYBL=0;
    AYBR=0;

    Vel_YFL=0.015;
    Vel_YFR=0.015;
    Vel_YBL=0.015;
    Vel_YBR=0.015;
else
    signA=sign(TableACC.AccY(13:14));
    [AYFL,I]=max(abs(TableACC.AccY(13:14)));
    AYFL=AYFL*signA(I);
    signA=sign(TableACC.AccY(29:30));
    [AYFR,I]=max(abs(TableACC.AccY(29:30)));
    AYFR=AYFR*signA(I);

```

```

signA=sign(TableACC.AccY(9:10));
[AYBL,I]=max(abs(TableACC.AccY(9:10)));
AYBL=AYBL*signA(I);
signA=sign(TableACC.AccY(25:26));
[AYBR,I]=max(abs(TableACC.AccY(25:26)));
AYBR=AYBR*signA(I);

%Velocity
signV=sign(TableVel.VY(13:14));
[Vel_YFL,I]=max(abs(TableVel.VY(13:14)));
Vel_YFL=Vel_YFL*signV(I);% Multiply by the sign of maximum value
signV=sign(TableVel.VY(29:30));
[Vel_YFR,I]=max(abs(TableVel.VY(29:30)));
Vel_YFR=Vel_YFR*signV(I);% Multiply by the sign of maximum value
signV=sign(TableVel.VY(9:10));
[Vel_YBL,I]=max(abs(TableVel.VY(9:10)));
Vel_YBL=Vel_YBL*signV(I);% Multiply by the sign of maximum value
signV=sign(TableVel.VY(25:26));
[Vel_YBR,I]=max(abs(TableVel.VY(25:26)));
Vel_YBR=Vel_YBR*signV(I);% Multiply by the sign of maximum value
end
if max(abs(TableACC.AccX)) > (max(abs(R_Table_Unc.AccX(c*32+1:32*C))))
    AXFL=0;
    AXFR=0;
    AXBL=0;
    AXBR=0;
    Vel_XFL=0.015;
    Vel_XFR=0.015;
    Vel_XBL=0.015;
    Vel_XBR=0.015;
else
    signA=sign(TableACC.AccX(19:20));
    [AXFL,I]=max(abs(TableACC.AccX(19:20)));
    AXFL=AXFL*signA(I);
    signA=sign(TableACC.AccX(23:24));
    [AXFR,I]=max(abs(TableACC.AccX(23:24)));
    AXFR=AXFR*signA(I);
    signA=sign(TableACC.AccX(3:4));
    [AXBL,I]=max(abs(TableACC.AccX(3:4)));
    AXBL=AXBL*signA(I);
    signA=sign(TableACC.AccX(7:8));
    [AXBR,I]=max(abs(TableACC.AccX(7:8)));
    AXBR=AXBR*signA(I);
    % 3- Velocity
    signV=sign(TableVel.VX(19:20));
    [Vel_XFL,I]=max(abs(TableVel.VX(19:20)));
    Vel_XFL=Vel_XFL*signV(I);% Multiply by the sign of maximum value
    signV=sign(TableVel.VX(23:24));
    [Vel_XFR,I]=max(abs(TableVel.VX(23:24)));
    Vel_XFR=Vel_XFR*signV(I);% Multiply by the sign of maximum value
    signV=sign(TableVel.VX(3:4));
    [Vel_XBL,I]=max(abs(TableVel.VX(3:4)));
    Vel_XBL=Vel_XBL*signV(I);% Multiply by the sign of maximum value

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```

        signV=sign(TableVel.VX(7:8));
        Vel_XBR=max(abs(TableVel.VX(7:8)));
        Vel_XBR=Vel_XBR*signV(I);% Multiply by the sign of maximum value
    end
    % ACC time series
        AYFL=timeseries(AYFL,T);
        AYFR=timeseries(AYFR,T);
        AYBL=timeseries(AYBL,T);
        AYBR=timeseries(AYBR,T);
        AXFL=timeseries(AXFL,T);
        AXFR=timeseries(AXFR,T);
        AXBL=timeseries(AXBL,T);
        AXBR=timeseries(AXBR,T);

    % Velocity Time series
        Vel_YFL=timeseries(Vel_YFL,T);
        Vel_YFR=timeseries(Vel_YFR,T);
        Vel_YBL=timeseries(Vel_YBL,T);
        Vel_YBR=timeseries(Vel_YBR,T);
        Vel_XFL=timeseries(Vel_XFL,T);
        Vel_XFR=timeseries(Vel_XFR,T);
        Vel_XBL=timeseries(Vel_XBL,T);
        Vel_XBR=timeseries(Vel_XBR,T);

    %-----%
    if NsFlag>1
        % Story 73
        % 1-Drifts
        if max(abs(DriftTable73.Drift_Y))>(max(abs(R_Table_Unc73.Drift_Y(c*32+1:32*C))))
            DYL73=0;
            DYR73=0;
        else
            DYL73=max(abs(DriftTable73.Drift_Y(13:14)));
            DYR73=max(abs(DriftTable73.Drift_Y(29:30)));
        end
        if max(abs(DriftTable73.Drift_X))>(max(abs(R_Table_Unc73.Drift_X(c*32+1:32*C))))
            DXF73=0;
            DXB73=0;
        else
            DXF73=max(abs(DriftTable73.Drift_X(19:20)));
            DXB73=max(abs(DriftTable73.Drift_X(3:4)));
        end
    end
    %%
    DYL73=timeseries(DYL73,T);
    DYR73=timeseries(DYR73,T);
    DXF73=timeseries(DXF73,T);
    DXB73=timeseries(DXB73,T);
    % 2- Accerations
    if max(abs(TableACC73.AccY))>(max(abs(R_Table_Unc73.AccY(c*32+1:32*C))))
        AYL73=0;
        AYR73=0;

        Vel_YL73=0.015;

```

```

    Vel_YR73=0.015;
else
    signA=sign(TableACC73.AccY(13:14));
    [AYL73,I]=max(abs(TableACC73.AccY(13:14)));
    AYL73=AYL73*signA(I);
    signA=sign(TableACC73.AccY(29:30));
    [AYR73,I]=max(abs(TableACC73.AccY(29:30)));
    AYR73=AYR73*signA(I);

    % Velocity
    signV=sign(TableVel73.VY(13:14));
    [Vel_YL73,I]=max(abs(TableVel73.VY(13:14)));
    Vel_YL73=Vel_YL73*signV(I); % Multiply by the sign of maximum value

    signV=sign(TableVel73.VY(29:30));
    [Vel_YR73,I]=max(abs(TableVel73.VY(29:30)));
    Vel_YR73=Vel_YR73*signV(I); % Multiply by the sign of maximum value
end
if max(abs(TableACC73.AccX)) > (max(abs(R_Table_Unc73.AccX(c*32+1:32*C))))
    AXF73=0;
    AXB73=0;

    Vel_XF73=0.015;
    Vel_XB73=0.015;
else
    signA=sign(TableACC73.AccX(19:20));
    [AXF73,I]=max(abs(TableACC73.AccX(19:20)));
    AXF73=AXF73*signA(I);
    signA=sign(TableACC73.AccX(3:4));
    [AXB73,I]=max(abs(TableACC73.AccX(3:4)));
    AXB73=AXB73*signA(I);
    % Velocity
    signV=sign(TableVel73.VX(19:20));
    [Vel_XF73,I]=max(abs(TableVel73.VX(19:20)));
    Vel_XF73=Vel_XF73*signV(I); % Multiply by the sign of maximum value

    signV=sign(TableVel73.VX(3:4));
    [Vel_XB73,I]=max(abs(TableVel73.VX(3:4)));
    Vel_XB73=Vel_XB73*signV(I); % Multiply by the sign of maximum value
end

% Time Series
AYL73=timeseries(AYL73,T);
AYR73=timeseries(AYR73,T);
AXF73=timeseries(AXF73,T);
AXB73=timeseries(AXB73,T);

% 3- Velocity
%
Vel_YL73=timeseries(Vel_YL73,T);
Vel_YR73=timeseries(Vel_YR73,T);

```

```

Vel_XF73=timeseries(Vel_XF73,T);
Vel_XB73=timeseries(Vel_XB73,T);
%-----%

% Story 70
% 1-Drifts
if max(abs(DriftTable70.Drift_Y))>(max(abs(R_Table_Unc70.Drift_Y(c*32+1:32*C))))
    DYL70=0;
    DYR70=0;
else
    DYL70=max(abs(DriftTable70.Drift_Y(13:14)));
    DYR70=max(abs(DriftTable70.Drift_Y(29:30)));
end
if max(abs(DriftTable70.Drift_X))>(max(abs(R_Table_Unc70.Drift_X(c*32+1:32*C))))

    DXF70=0;
    DXB70=0;
else
    DXF70=max(abs(DriftTable70.Drift_X(19:20)));
    DXB70=max(abs(DriftTable70.Drift_X(3:4)));
end
% %
DYL70=timeseries(DYL70,T);
DYR70=timeseries(DYR70,T);
DXF70=timeseries(DXF70,T);
DXB70=timeseries(DXB70,T);
% 2- Accerations
if max(abs(TableACC70.AccY))>(max(abs(R_Table_Unc70.AccY(c*32+1:32*C))))
    AYL70=0;
    AYR70=0;

    Vel_YL70=0.015;
    Vel_YR70=0.015;
else
    signA=sign(TableACC70.AccY(13:14));
    [AYL70,I]=max(abs(TableACC70.AccY(13:14)));
    AYL70=AYL70*signA(I);
    signA=sign(TableACC70.AccY(29:30));
    [AYR70,I]=max(abs(TableACC70.AccY(29:30)));
    AYR70=AYR70*signA(I);

    % Velocity
    signV=sign(TableVel70.VY(13:14));
    [Vel_YL70,I]=max(abs(TableVel70.VY(13:14)));
    Vel_YL70=Vel_YL70*signV(I) % Multiply by the sign of maximum value

    signV=sign(TableVel70.VY(29:30));
    [Vel_YR70,I]=max(abs(TableVel70.VY(29:30)));
    Vel_YR70=Vel_YR70*signV(I) % Multiply by the sign of maximum value

end
if max(abs(TableACC70.AccX))>(max(abs(R_Table_Unc70.AccX(c*32+1:32*C))))
    AXF70=0;

```

```

AXB70=0;

Vel_XF70=0.015;
Vel_XB70=0.015;
else
    signA=sign(TableACC70.AccX(19:20));
    [AXF70,I]=max(abs(TableACC70.AccX(19:20)));
    AXF70=AXF70*signA(I);
    signA=sign(TableACC70.AccX(3:4));
    [AXB70,I]=max(abs(TableACC70.AccX(3:4)));
    AXB70=AXB70*signA(I);
    % Velocity
    signV=sign(TableVel70.VX(19:20));
    [Vel_XF70,I]=max(abs(TableVel70.VX(19:20)));
    Vel_XF70=Vel_XF70*signV(I); % Multiply by the sign of maximum value

    signV=sign(TableVel70.VX(3:4));
    [Vel_XB70,I]=max(abs(TableVel70.VX(3:4)));
    Vel_XB70=Vel_XB70*signV(I); % Multiply by the sign of maximum value

end

% Time Series
AYL70=timeseries(AYL70,T);
AYR70=timeseries(AYR70,T);
AXF70=timeseries(AXF70,T);
AXB70=timeseries(AXB70,T);

% 3- Velocity
%
Vel_YL70=timeseries(Vel_YL70,T);
Vel_YR70=timeseries(Vel_YR70,T);
Vel_XF70=timeseries(Vel_XF70,T);
Vel_XB70=timeseries(Vel_XB70,T);
end

%-----%
% Assign Optimum FIS in Each Direction
MDriftY=max(abs(R_Table_Unc.Drift_Y(c*32+1:32*C))) % max drift in Y direction @
step C
MDriftX=max(abs(R_Table_Unc.Drift_X(c*32+1:32*C)));
MAccY=max(abs(R_Table_Unc.AccY(c*32+1:32*C)));
MAccX=max(abs(R_Table_Unc.AccX(c*32+1:32*C)));
fControlY=GetOpFIS(FISmem,MDriftY,MAccY,maxD_Y,Des_acc);
fControlX=GetOpFIS(FISmem,MDriftX,MAccX,maxD_X,Des_acc);
% Simulation For FL Controller and MR Damper
sim('MRFLConline.slx');
disp(['Iteration ',num2str(C),' is Completed'])
R_Table(c*32+1:32*C,:)=[DriftTable(1:32,:),TableACC(1:32,:),TableDis(1:32,:)]
TableVel(1:32,:); %16 points and 2 steps(max & min) begins from zero
V_Table(C,:)=[VFYFL(1001),VFYFR(1001),VFYBL(1001),VFYBR(1001),VFXFL(1001),VFXFR
(1001),VFXBL(1001),VFXBR(1001)];
c=c+1;

```

```

clear DriftTable TableACC TableVel TableDis

%% Initial parameters of the Optimization algorithm
max_iter=1;
N=5;
ArchiveMaxSize=50;
dim=110;
obj_no=2;

%% ----- MOMVO -----

%% Search in space to get optimized value for FL in Y direction
[Best_universe_scoreY,Best_universe_posY,Archive_FY]=MOMVOWI(max_iter,N,
ArchiveMaxSize,C);
[Best_universe_scoreX,Best_universe_posX,Archive_FX]=MOMVOWIX(max_iter,N,
ArchiveMaxSize,C);
%% FIS Memory Updating
[~,I]=sort(FISmem(:,112));
FISmem=FISmem(I,:);
[~,I]=sort(FISmemX(:,112));
FISmemX=FISmemX(I,:);

if all(Best_universe_scoreY<=FISmem(memSize,111:112)) && any(
Best_universe_scoreY<FISmem(memSize,111:112))
    FISmem(memSize,:)=[Best_universe_posY,Best_universe_scoreY];
end
if all(Best_universe_scoreX<=FISmemX(memSize,111:112)) && any(
Best_universe_scoreX<FISmemX(memSize,111:112))
    FISmemX(memSize,:)=[Best_universe_posX,Best_universe_scoreX];
end

fprintf('Optimization was done for load step  %0.0f \n',C);

end
save('OnlineFLMVO.mat','FISmem','FISmemX','R_Table','V_Table','F_Table');

```

LIST OF PUBLICATIONS

Abdulateef, W. S., & Hejazi, F. (2023). Fuzzy logic based adaptive vibration control system for structures subjected to seismic and wind loads. *Structures*, 55(January), 1507–1531. <https://doi.org/10.1016/j.istruc.2023.06.108>

Abdulateef, W. S., & Hejazi, F. (2024). Adaptive Real Time Efficient Control Algorithm for Buildings Under Wind and Earthquake Forces. In *International Journal of Civil Engineering* (Vol. 1). Springer International Publishing. <https://doi.org/10.1007/s40999-024-00990-1>

