MR Dampers in Smart Structures with Nonlinear Non-affine Dynamics improvising Intelligent Control

By

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Executive Summary

The increasing complexity of high-rise buildings, cable-stayed long-span bridges, deep-sea offshore structures or suspension systems demands effective tools for control and health monitoring. These infrastructure systems are usually integrated with actuation, sensing, computation resources and information networks, taking advantage of the synergy of civil engineering and mechatronics in an emerging area called *civiltronics*. Towards the achievement of high performance smart structures, semi-active vibration control in complex civil structures has been very promising, particularly in the mitigation of external excitations and dynamic loadings owing to its meritorious features of low cost, strong robustness and high reliability against various loading sources. Structural behavior and energy efficiency can be improved via directly controlling the input of the smart devices. For example, semi-active controlled dampers, from the dissipation point of view by using suitable control schemes for parameterized relationships describing the system dynamics of the structure integrated with the smart devices with respect to the applied electrical signal. This research is concerned with the problem of controlling the nonlinear, non-affine dynamics of smart structures with magneto-rheological (MR) dampers. A laboratorial set-up of a one-storey steel frame and a benchmark five-storey building model integrated with MR dampers are used in this research. These smart structures are subject to scaled earthquake vibrations excited by a shake table. A static hysteresis model is adopted for the MR damper, in which current-dependent nonlinear functions are used to represent the damper force-velocity characteristics. Here the semi-active control problem of the smart structure system is formulated in current-input non-affine nonlinear state space equations. The complications in the design are tackled by using intelligent control, whereby adaptive fuzzy logic control is proposed to deal with nonlinearity of the control dynamics and non-affinity in the control input, assuming the availability of the displacement and velocity information of the last floor. Here, self-organising adaptive fuzzy logic control is developed to prevent cases that the resulting fuzzy inference system may be unnecessarily large or too small to adequately represent the complex dynamics of the smart structure under control. The main objectives of this research are thus to model the overall smart structure system and to develop self-organising adaptive fuzzy logic schemes for the continuous-time multiple-input multiple-output uncertain nonlinear dynamics of the structure. The proposed control algorithms are implemented in MATLAB and SIMULINK. To illustrate their effectiveness in seismic vibration suppression of civil structures due to earthquake excitations, simulation results are presented together with discussions on performance evaluation and further remarks on the implementation aspects.

CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that the work in this thesis has not been submitted for a similar degree nor has it been submitted as part of requirements for any other degree.

I also certify that the thesis has been written by me. Any help I have received in my research work and the preparation of this thesis itself has been acknowledged. In addition, I certify that all the information sources and literature used are referenced in the thesis.

Zeinab Movassaghi

This thesis is especially dedicated to my dearest father, mother, sisters and brother
for their love, blessings and encouragement.

PUBLICATIONS

The following technical papers have been published based on the work of this thesis:

1. Movassaghi, Z., Ha, Q., Samali, B., "A Self-structuring Adaptive fuzzy Control Scheme for Non-affine nonlinear systems used in Smart Structures", *Sixth International conference on Structural Health Monitoring of Intelligent Infrastructure (ISHMII-6)*, Hong Kong, 9-11 December, 2013
2. Movassaghi, Z., Samali, B., Ha, Q., "Smart Structures Embedded with MR dampers Using Non-Affine Fuzzy Control", *22nd Australasian Conference on the Mechanics of Structures and Materials (ACMSM)*, Sydney, Australia, 11-14 December 2012
3. Royel,S., Movassaghi, Z., Kwok, N., and Ha,Q., "Structural control Using MR dampers with Second Order Sliding Mode Controller", *Proceedings of the 1st international conference on control automation and information sciences (ICCAIS),* Ho Chi Minh City, Vietnam, 26-29 November 2012
4. Movassaghi, Z., "Considering Active Tuned mass dampers in two different structures", *Australian Control Conference (AUCC),* Sydney, Australia, 15-16 November 2012
5. Movassaghi, Z., Samali, B., Ha, Q., "Adaptive Neuro-Fuzzy Modelling of a high-rise structure equipped with an Active Tuned Mass Damper", *6th Australasian Congress on Applied Mechanics, ACAM 6,* Perth, Australia, 12-15 December 2010

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NOTATIONS

A System matrix

B Input matrix for control

C Output matrix

D Matrix to represent direct coupling between input and output for control force

E Input matrix for wind/earthquake excitations

F Matrix to represent direct coupling between input and output for wind/earthquake excitations

J_1-J_6 Evaluation criteria

J Performance index

u Control force

v Measured noise vector

W External excitations (wind/earthquake)

x State vector (in the control matrix)

$\mathbf{x}(t)$ Displacement of the storey

$\dot{\mathbf{x}}(t)$ Velocity of the storey

$\ddot{\mathbf{x}}(t)$ Acceleration of the storey

$\ddot{\mathbf{x}}_g$ Ground acceleration

y Measured output vector

z Controlled output vector

M Mass matrix

C Damping matrix

K Stiffness matrix

CHAPTER 1

INTRODUCTION

1.1. Problem Statement

The increasing demand for high-rise building structures, cable-stayed long-span bridges, deep-sea offshore structures or suspension systems that are integrated with actuation, sensing, computation resources and information networks demand effective tools for control and health monitoring.

In the recent century, widespread catastrophic effects have been seen due to severe earthquakes. Damage due to such excitations can be destructive which indicates the need for more effective methods of earthquake protection.Towards the achievement of high performance smart structures, vibration control in complex civil structures has been very promising, particularly in the mitigation of external excitations and dynamic loadings owing to its advantages of low cost, robustness and reliability against various loading sources and integration of actuators, sensors, computing and signal processing units. Control performance and energy efficiency can be improved via direct input control of smart devices from the dissipation point of view by using parameterized relationships describing the damper dynamics with respect to the applied electrical signal and integrate their models into structural dynamics.

Various passive and active vibration control strategies have been proposed to mitigate the seismic response of structures due to these destructive excitations. The goals of these methods are to increase the period of the structure (increase flexibility) beyond that of the earthquake or to add damping. Even though many of these strategies have been applied, set backs are encountered regarding the cost, reliance on external power, robustness and mechanical intricacy.

Semi-active control devices are being examined by researchers around the world as a means of mitigating the dynamic effects of seismic loads on civil engineering structures (Symans & Constantinou 1999). These devices have attracted significant attention recently because they provide controllable damping characteristics in a device that is inherently stable and has minimal power requirements. Currently devices in this class appear to offer the best opportunity for widespread acceptance of these innovative control techniques by the civil engineering community. Examples of such devices include variable orifice fluid dampers, variable friction dampers, adjustable tuned liquid dampers and controllable fluid dampers. Magneto Rheological (MR) dampers are classified as controllable fluid devices (Spencer et al. 1997). These devices have demonstrated a great deal of promise for civil engineering applications in studies. Both experimental and analytical studies have demonstrated that the performance of MR dampers is superior to that of comparable passive and active control systems.

Due to the high nonlinearity of MR devices, one of the main challenges in the application of this technology is in the development of suitable control algorithms. A variety of semi-active control algorithms have been developed, including Lyapunov, decentralized bang-bang, modulated homogeneous friction, bi-state control, fuzzy logic control methods (Sun & Goto 1994), adaptive nonlinear control and clipped-optimal. Previous analytical investigations of a selection of these algorithms have demonstrated that the performance of control systems based on MR dampers is highly dependent on the choice of algorithms employed (Jansen & Dyke 2000).

In this study, fuzzy logic controllers are proposed for the control. They have shown to be especially effective in the control of mathematically ill-understood processes; fuzzy logic controllers thus can address directly important issues of intelligent control such as robustness and conformability to the linguistic rules (Tong, Li & Chai 1999).

An adaptive fuzzy controller can be defined as a controller, in which adaptive fuzzy systems are employed and adaptive control theory is used to derive training algorithms such that stability and performance of the closed-loop system are guaranteed. Lyapunov stability techniques play a critical role in the design and stability analysis of the adaptive systems. A Lyapunov function candidate is a mathematical function designed to provide a simplified scalar measure of the control objectives. The control objectives are met when the chosen Lyapunov function is driven to zero.

Now, fixed-structured adaptive fuzzy logic control (Wang 1994) requires designers to choose the rule base and membership functions by trial and error. This task is not trivial as long as exact mathematical models of plants are not known. Quite often, the structure used is either unnecessarily large or too small to adequately represent a plant.

From this perspective, self-structuring adaptive fuzzy logic control is more advantageous as it can automatically add and remove rules from a fuzzy system. Park et al (Park, Park, et al. 2005b) proposed a self-structuring fuzzy system, in which rules are added to the rule base when exploring the input space. However no mechanism to remove rules is proposed therein. Gao and Er (2003) proposed a self-organizing fuzzy neural system, in which rules are generated using the system error and ε completeness and an error reduction ratio concept is used for rule pruning. In (Phan & Gale 2008), a self-organising adaptive fuzzy logic controller is presented, which employs the system error, the ε-completeness and a simple algorithm to replace rules.

1.2. Objectives and scope of the Thesis

This research is concerned with a numerical analysis of a one and five storey steel structure integrated with a pair of Magneto Rheological (MR) dampers in addition to fuzzy logic controllers. The building structural model is subject to scaled earthquake records. The static hysteresis model is adopted for the MR damper, in which nonlinear functions are used to represent hysteresis in the damper characteristics. In this thesis, the current-controlled problem of the smart structure system is formulated in non-affine state space equations. Adaptive fuzzy logic control is proposed to deal with nonlinearity of the control dynamics and non-affinity in the control input, assuming the availability of the input of the fuzzy logic controller. Most adaptive fuzzy logic controller schemes employ fuzzy inference systems with fixed structures. In which, a designer must specify the number of membership functions and the rule base by trial and error. In many cases, this task is not trivial as exact mathematical models of plants are generally not known. Thus, it is often known that the fuzzy inference system used is unnecessarily large or too small to adequately represent the plant. Therefore, self-organising adaptive fuzzy logic control is proposed in this thesis to overcome this setback. To illustrate the effectiveness of the proposed control scheme on seismic vibration suppression of the structures due to earthquake excitations, simulation results are presented together with discussions on its evaluation and further remarks on the implementation aspect.

1.3. Contribution of this thesis

The development of this thesis is firstly focusing on the fixed adaptive fuzzy logic control which requires designers to choose the rule base and membership functions by trial and error. Then, the main contribution of this research is to design self-organising adaptive fuzzy logic controllers as it can automatically add and remove rules from a fuzzy inference system. This contribution is of significance, given the nonlinearity and non-affinity of the structural control system model.

1.4. Thesis Layout

Chapter one gives a background of the research project, outlines the objectives of this research study and the approaches taken.

Chapter two details most of the related literature review for this study. It begins with a detailed description of passive and active vibration control systems and then moves on to semi-active vibration control systems and focuses on their advantages compared to the active and passive ones. This chapter also focuses on MR fluids and devices and its applications. Modelling and control of MR dampers are also discussed. In the final section of this chapter, the control algorithms used to drive the active or semi-active control system are described. It starts with the description of Lyapunov and linear quadratic regulator (LQR) and then a brief review on fuzzy logic control is presented.

Chapter three considers active tuned mass dampers in two different structures, five and fifteen storey structures. Different mass ratios (mass of ATMD/mass of total structure) ranging from 1 to 4% have been assumed for the two structures and the seismic vibration reduction (displacement of the last storey) is compared in different cases. In another case, two ATMDs are installed in different floors for both the two structures and the displacement of the last storey is seen to be reduced in different cases.

Chapter four describes the application of multiple tuned mass dampers (MTMD) in two different structures, five and fifteen storey structures. The reduction in displacement of the last storey is compared in different scenarios; a sole ATMD on the top floor, multiple ATMDs with equal and non-equal mass on the top floor, both for the five and fifteen storey structures.

Chapter five describes self-organising adaptive fuzzy logic controllers. A description is presented along with its application in affine and non-affine nonlinear systems. Numerical examples are provided to further explain the approach.

Chapter six focuses on the description of controlled buildings and excitations, the equation of motion of the structure with semi-active vibration suppression devices is given and the non-affine nonlinear equations encountered are discussed. In addition, the simulation of a one and five storey structure embedded with MR dampers and earthquake excitations are subjected on it. The design of fuzzy logic controller is compared to self-organising adaptive fuzzy logic controller. Simulation results of this one and five storey structure are presented. Some evaluation criteria are defined to compare the results with an uncontrolled structure with no MR damper and no controller.

Chapter seven discusses the final conclusions of this thesis and further considerations for future researches.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

Building structures subjected to external loads; earthquake or wind induce catastrophic vibrations in the structure which may result in severe damage and reduce the durability. Therefore, it is important to ensure the safety of the occupants inside the structure and the structure itself by mitigating or controlling these vibrations. To achieve this, different types of control devices are developed over the past few decades and still are the focus of research. Yao (1972) developed the concept of structural control, and this idea has been adopted and applied in different types of structures.

Soong (Soong 1990) suggested to consider four main criteria in order to develop any structural control system. These are as follows:

- Nowadays many high rise structures are constructed to accommodate the increasing population. Therefore, these structures are very stiff and unable to reduce the vibration under the extreme environmental load. Hence, the flexibility of the structure needs to be increased to mitigate the effect of external load on it.
- The high rise buildings are usually complex and also expensive which requires the increase of safety levels.
- It is essential to ensure the best performance of the building in terms of serviceability and strength within the safety limits.
- The materials should be used in such a way that it is cost efficient and safe.

In USA and Japan, extensive usages of structural control devices are observed for buildings and bridges. The structural control system is a multi-disciplinary area which covers the field of wind and earthquake engineering, structural dynamics, control theory, sensing technology, computer science, data processing and material science.

The main idea of the structural control system is to change the property of the structure when it is subjected to earthquake excitation in order to withstand the external load safely. This can be attained by reducing the excitation subjected to the structures or by providing additional damping device for the dissipation of energy. The structural control system can be categorised as following

- Passive vibration control devices: To operate this system, it is not required to have external power supply.
- Active vibration control devices: External power supply is essential in significant amount for the functional operation of the system.
- Hybrid vibration control devices: It combines both the passive and active devices.
- Semi-active vibration control system: Only an optimum amount of external power is required to run this system and therefore, can be considered as a compromise of passive and active control system.

Frequency is the key parameter for the structural control devices and classification of the system is illustrated in figure 2.1. Both the frequency dependent and frequency independent systems are used as control devices as shown in the figure. Frequency dependent systems dissipate the energy of the excitation subjected on the structure and are independent of the natural frequency of the structure. The frequency dependent can be further divided into resonant and non-resonant types that can prevent resonance. Tuned mass damper and hybrid mass damper are considered as resonant type whereas base isolation and active variable stiffness are the examples of non-resonant types since they reduced the energy produced by the earthquake. Frequency independent system is subdivided into passive, active and semi-active devices. Viscous damper is a passive control device, while active mass driver and active tendon are categorised as active control devices due to producing counteracting control forces using external energy supplied. Some examples of frequency independent semi-active devices are controllable fluid (electro rheological/ER, magneto rheological/MR) damper, variable friction damper, variable orifice damper, etc.

Different control algorithms are available to implement for controlling the structures (Friedland 1986; Leipholz & Abdel-Rohman 1986; Nguyen 1998; Ogata 1967, 1987; Ogata & Yang 1970). A control system commands the device installed in the structure to regulate it and also to control itself. A control system is comprised of actuators, controllers, sensors, plants, etc. and can be applied in a building, bridge, heating furnace or even in a chemical reactor. A control algorithm defines the specification of the control signal that operates in each time interval, and it is influential to different factors including stability, reliability, economy, efficiency and performance. Consequently, control algorithm is considered as the

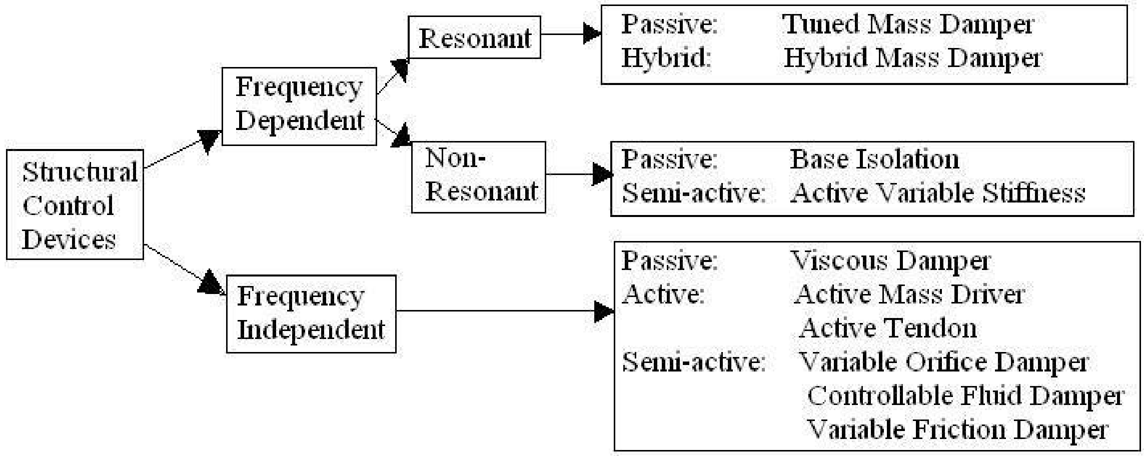


Figure 2.1. Classification of Structural control Devices

key element for any structural control system. Depending on the requirements of the structures, a selection of control algorithm may differ and hence, various control algorithms are available. For instance, linear quadratic regulator (LQR), sliding mode control, neural networks (NN), fuzzy logic controls (FLC) are widely used control algorithms.

This chapter describes the concept of different structural vibration control systems, development of the control devices and the control algorithms. As this research project mainly focuses on the semi-active vibration control system and therefore, a brief explanation of this system will be presented in the later section of the chapter.

2.2. Passive vibration control systems

The prime goal of the passive vibration control system is to reduce the structural response by dissipating the energy which is achieved by improving the motion of the structure in order to produce relative motions within the passive devices. The energy dissipation capacity influences the amplitude of the vibration which needs to be controlled. A control system with large energy dissipation capacity will reduce the amplitude of the vibration to a great extent. The increase in energy dissipation capacity can be achieved by different methods which results in enhancing the performance of the passive vibration control system.

The difference between a conventional structure and a structure with a vibration control system is demonstrated in figure 2.2. A conventional structure cannot control the vibration due to the increase in energy from the earthquake. Subsequently, there is a direct effect on the structure that may lead to the collapse of the structure. In contrast, the earthquake energy can be dissipated substantially if a passive vibration control system is installed in the structure. The advantage of this passive control is that it does not need any external power supply. However, the limitation of this system is the inability to modify the mechanical properties of it when required.

To ensure the safety of the structure, the research in the field of passive vibration control devices has a long history that dates back to *70* years. It started with making the first storey of a high rise building flexible by removing the shear walls in that floor which isolate the upper storey subjected to large dynamic shear forces during an earthquake. Later, different base isolation systems were developed by a number of researchers (Asher 1994; Foutch 1994; Samali 2000b-b, 2002c; Wu Yi Min 2000) based on increasing the flexibility between the sub and super structure. This was achieved by placing horizontal pads in the foundation that provoke lateral slip between the base of the structure and foundation.

Two types of base isolation systems are generally used namely elastomeric bearings and sliding systems (*National Information Service for Earthquake Engineering, University of California, Berkeley* 2002). The elastomeric bearings have low horizontal stiffness and are consist of natural rubber or neoprene. It is placed between the foundation and the structure that decoupled the structure from the lateral component of the earthquake. This result in lowering the fundamental frequency compared to the fixed base one. Therefore, this system changes the dynamic property of the structure rather than absorbing the energy and as a result, the resonance can be avoided. On the other hand, the sliding systems restrict the amount of shear transfer through the isolation interface. Sand, frictional pendulum etc. can be used as sliding system and have been used in China and USA.

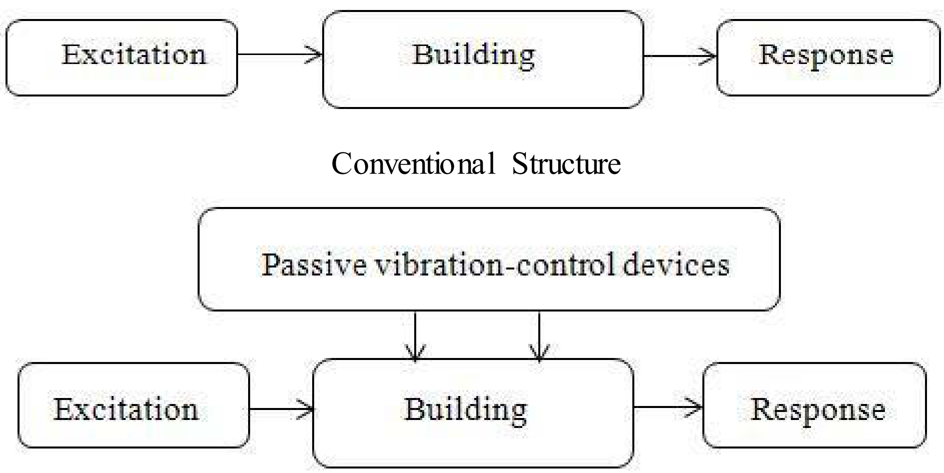


Figure 2.2. Conventional (top figure) and Passive (bottom figure) vibration control system

The base isolation system has been applied to many structures across the world over the last two decades. Figure 2.3 shows the first base isolated building built in USA in 1985 which was the office of Foothill community law and justice centre. This was a four storey frame structures incorporating braced frames in some bays to stiffen the building and also, a basement and sub-basement for the isolation system. There were a total of 98 isolators of multi-layered natural rubber bearings in this base isolation system. The system was reinforced with steel plates. Another application of base isolation system is the University of Southern California teaching hospital, Los Angeles (1991), which is an eight storey braced steel frame. It consists of 68 lead rubber isolators and 81 elastomeric isolators. During the Northridge earthquake in 1994, this building performed well which explains the effectiveness of the system.

Foothill Communities and Justice Centre (1985) University of Southern California Teaching Hospital (1991)

Figure 2.3. Example of base isolated structures

Besides USA, Japan also implemented base isolation systems, and the first one constructed was the Yachiyo-Dai House (1983). By the end of 1998, there were approximately 550 base isolation building built in the USA and Japan, respectively. The Matsumura-Gumi research laboratory and the West Japan postal savings computer centre are also examples of base isolation systems and survived the destructive Kobe earthquake in Japan.

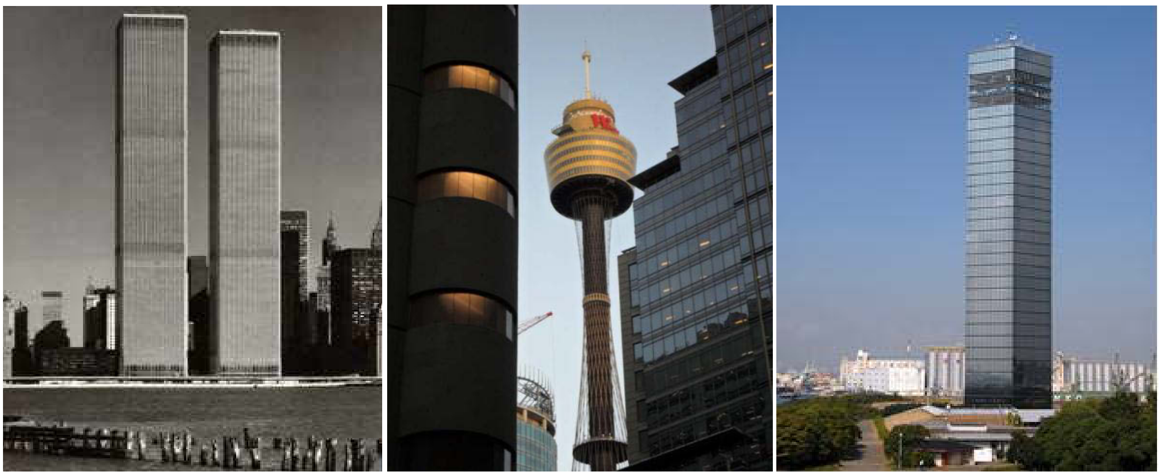
The Utah state capitol in USA, finished in 2008 is shown in figure 2.4. It stands in an earthquake zone where seismic monitoring stations record more than 700 earthquakes each year. This is a monumental, four storeys, reinforced concrete building with granite cladding and a large copper-clad concrete dome. The base isolation system consists of 265 isolators, each weighing 5000 pounds.

Figure 2.4. Utah state capitol in USA

Other passive control devices dissipate the energy in two stages. In the first stage, kinetic energy is converted to heat while in the second stage, energy is transferred between vibrating modes by incorporating dynamic vibration absorbers. Metallic yield dampers, friction dampers, viscoelastic dampers and viscous fluid dampers dissipate the energy of earthquakes through inelastic deformation of metals in contrast to tuned mass dampers and tuned liquid dampers which dissipate kinematic energy through friction mechanisms. The research related to metallic yield dampers can be found in (Aiken, Nims & Kelly 1992; Bergman, Goel & Power 1987; Kelly 1972; Martinez-Romeo 1993; Perry et al. 1993; Sakurai et al. 1992; Skinner 1975 ; Skinner 1980; Tsai et al. 1993; Whittaker et al. 1991) and application and theory of friction dampers are available in (Aiken 1988, 1990; Filiatrault & Cherry 1987; Filiatrault & Cherry 1990; FitzGerald et al. 1989; Grigorian, Yang & Popov 1993; Li & Reinhorn 1995; Pall & Marsh 1982; Tsiatas & Daly 1994).

Viscoelastic dampers dissipate the energy through shear deformation of the viscoelastic layers, and the research on the development of this damper can be found in (Chang et al. 1993; Foutch 1993; Kasai et al. 1993; Makris & Dargush 1994; Nielsen et al. 1996; Shen 1995; Soong & Lai 1991; Soong & Dargush 1997; Tsai 1993b; Zhang 1992; Zhang, Soong & Mahmoodi 1989). This damper was used in the twin tower of the world trade centre, as shown in figure 2.5, with a number of 10,000 viscoelastic dampers. Another passive damper namely viscous fluid damper consists of a piston in the damper housing filled with viscous fluid. This system dissipates the energy through the movement of the piston in the highly viscous fluid (Arima 1988; Hirari 1994; Makris 1991b, 1991a; Miyazaki 1992).

Tune mass damper (TMD) is a widely used passive control system mostly applied for the tall buildings. The mass of this damper is usually equal to the 1% of the total mass of the structures and installed at the top of the building by means of spring. The primary goal of TMD is to increase the damping of the structure by tuning it with the primary structure. A number of research were conducted, both numerically and experimentally, to determine the efficiency of TMD and concluded that the effectiveness varies with earthquakes (Villaverde 1994). TMD can reduce the vibration of the fundamental mode given that it is tuned with the first natural frequency of the structure. However, the higher order modes may suppress slightly or may even amplify. To overcome this limitation, Clark (Clark 1988) proposed the use of multiple tuned mass dampers where each one is tuned to a different dominant frequency. It is important to consider the amount of added on the top of the building and also the movement of TMD relative to the building while designing it. The research on the improvement of TMD is available in (Li, Shen & Choo 1994; Matsuhisa 1994; Setareh 1994; Xu 1992; Yamaguchi & Harnpornchai 1993). Some application of TMD can be found in Sydney centre point tower (Australia), the Citicorp centre in New York City and the John Hancock tower in Boston (USA) and Chiba port tower (Japan), as shown in figure 2.5.



World Trade Centre (1969) Centre point Tower (1980) Chiba Port Tower (1986)

Figure 2.5. Example of structures equipped with Viscoelastic damper and tuned mass damper

The Tokyo Skytree, as shown in figure 2.6, is a broadcasting, restaurant, and observation tower in Tokyo, Japan. It became the tallest structure in Japan in 2011, with a full height of 634.0 metres (2,080 ft). Two types of vibration control system are used in this structure; TMDs on the top and the Core Column System. As a tower that is used for terrestrial digital broadcasting, it is necessary to suppress the wind response of the gain tower at the top of the tower on which the broadcasting antennae are installed. Specifically, the velocity of the oscillations of the gain tower due to normal wind, which has a high frequency of occurrence, was required to be maintained less than a specified value. For this purpose two TMDs were installed on the top of the tower.

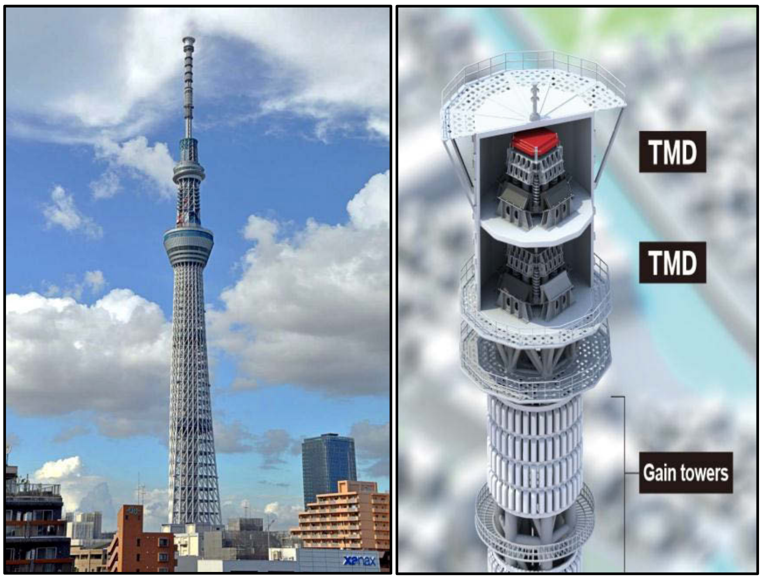


Figure 2.6. Tokyo Skytree

Tuned liquid damper (TLD) and tuned liquid column damper (TLCD) are also passive vibration control devices where structural energy is absorbed by the viscous actions of the fluid in TLD, and the dissipation of energy is attained by the passage of liquid through an orifice in TLCD. The performance of TLD and TLCD in a building is reported in (Fujino et al. 1988; Mayol 2002; Samali 2000b-a, 2000a; Tamura 1995; Yeh 1996b).

One Wall Centre, as shown in figure 2.7, also known as the Sheraton Vancouver Wall Centre hotel, is a 48-storey skyscraper hotel with residential condominiums in Vancouver, Canada which was completed in 2001. To counteract possible harmonic swaying during high winds, this structure has a tuned water damping system at the top level which consists of two specially designed 50,000-imperial-gallon (60,000 U.S. gal; 227,300 L) water tanks. These tanks are designed so that the harmonic frequency of the sloshing of the water in the tanks counteracts the harmonic frequency of the swaying of the building.

Figure 2.7. One Wall Centre in Vancouver, equipped with tuned liquid dampers at the top storey

Even though the passive vibration control system is stable and reliable in comparison to the active vibration control system, it is highly dependent on the type of earthquake. For instance, the system designed for Northridge earthquake cannot be used for Kobe earthquake. Therefore, this system is always efficient for certain critical situation.

2.3. Active vibration control devices

Active vibration control systems need external power supply to dissipate the energy produced from an external source and also to develop the control force. The mechanical properties of this system changes based on the feedback received from the structure. After the discovery of mitigating the dynamic response using vibration control devices, the active control systems were proposed and developed (Yao 1972). The schematic diagram of this system is presented in figure 2.8. The basic steps of this system can be divided in three phase. Firstly, the structures will response due to any external excitation which is followed by capturing it from the sensors attached at different levels. The last stage is the post processing of the data, acquired from the sensors using computer controller, to send a command to the actuators in order to produce the required control forces.

In general, control system can be classified into two categories based on the regulation of the control force, as shown in figure 2.9. Feedback control or in other words, closed loop control measures the structural response variables to monitor it continuously to update the applied control forces. Another type is called feed forward control or closed loop control where the control force is dependent on the output. A closed-open loop control or feedback-feed forward control is defined as utilizing both the structural responses and external excitation in the control design development phase.

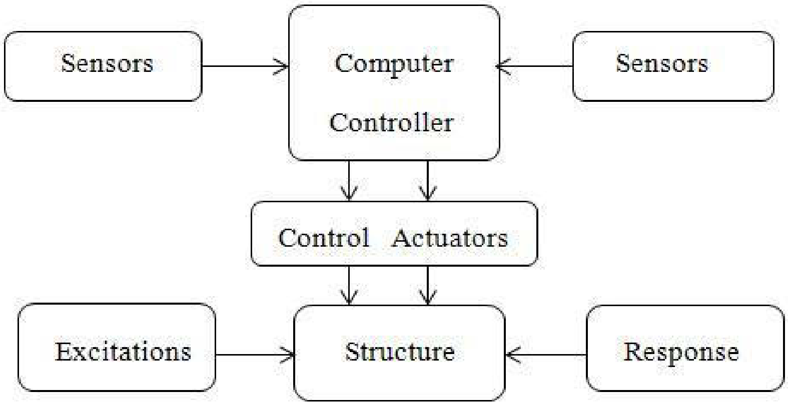


Figure 2.8.Active vibration control system Diagram

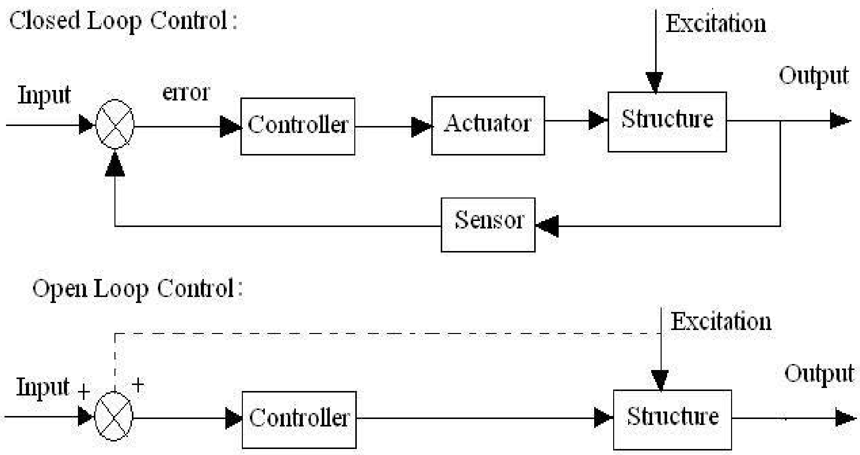


Figure 2.9. Control System Block Diagram

Similar to the passive vibration control system, several researches were carried out to develop the control algorithms for active vibration control systems in order to enhance the performance of the control system. Different active vibration control devices can be found in the literature and also in the application, such as, pulse control (Masri 1980, 1981; Miller et al. 1988; Reinhorn, Manolis & Wen 1987; Udwadia 1981), active bracing (Dyke et al. 1995; Loh, Lin & Chung 1999), active tendons (Abdel-Rohman & Leipholz 1983; Agrawal, Yang & Wu 1998; Samali, Yang & Liu 1985; Soong et al. 1991; Spencer, Dyke & Deoskar 1998; Yang 1982; Zhang et al. 1993), active mass damper(Adhikari 1998; Hoare 1994; Kobori et al. 1991; Koshika et al. 1992; Samali 2000c; Suhardjo, Spencer Jr & Kareem 1992), etc.

To specify a control strategy for determining required control force applicable to the structure, control algorithm plays a vital role. Therefore, this is an important area of research, and so, many researchers developed and proposed different control algorithms depending on the requirements, which includes, Linear quadratic regulator/LQR(Yang 1982),(Abdel-Rohman & Leipholz 1983),(Chang & Soong 1980; Chung, Reinhorn & Soong 1988; Ikeda 1998; Indrawan et al. 1994; Soong et al. 1991; Watanabe 1992; Yang, Li & Vongchavalitkul 1994),(Soong & Spencer Jr Reviewer 1992), robust control (Dyke, Spencer Jr, Quast, et al. 1996; Spencer Jr, Suhardjo & Sain 1994; Suhardjo, Spencer & Sain 1990; Yoshida 1998), sliding mode control (Adhikari 1998; Cai et al. 2000; Edwards & Spurgeon 1998; Jianchun & Bijan 2002; Li 2001; Singh 1998; Yang, Wu & Agrawal 1995a, 1995b; Yang et al. 1997; Yang et al. 1996; Yang 1994b, 1994d; Yang et al. 1994), adaptive control (Baba 1998; Smith, Burdisso & Suarez 1994) neural network control (Bani-Hani & Ghaboussi 1998; De Stefano 1999; Ghaboussi & Joghataie 1995; Hung, Kao & Lee 2000; Hung & Lai 2001), nonlinear control (Agrawal & Yang 1997; Agrawal & Yang 1996; Hatada 1998; Spencer et al. 1996), fuzzy logic control (Al-Dawod et al. 1999a, 1999b; Aldawod et al. 1999; Aldawod et al. 2001; Casciati & Giorgi 1996; Kawamura & Yao 1990; Naghdy et al. 1998; Samali & Al-Dawod 2003), etc.

Due to the advantages of utilising active vibration control system for full scale application, many structures can be found across the world equipped with active vibration control devices. The first building was built in Tokyo in 1989, named Kyobashi Seiwa building, as shown in figure 2.7. This is an11 storey commercial building equipped with two active mass dampers as vibration control devices which are a pendulum type dual mass system. These dampers are able to control lateral and torsional vibration excited from moderate earthquake or strong wind. Another application of this system can be observed at Riverside Sumida central tower in Tokyo, completed in1994. This is a 33 storey building and equipped with two active mass dampers placed at the roof of the tower (Suzuki et al. 1994; Watanabe et al. 1994).

In comparison to passive vibration control systems, the efficiency of the active vibration control systems is more beneficial in terms of its capability to control the structural response at any desired level. Additionally, the influences of ground motion, geographical and site location have less effect on this system. The biggest concern and shortcoming of this system is the requirement of a large amount of external power supply which may be unavailable during a strong earthquake and will eventually lead to the system failure.

2.4. Hybrid vibration control devices

Hybrid vibration control system utilizes the benefits of the passive and active vibration control system in order to overcome the shortcomings of these two systems, and therefore, perform better than passive and active vibration control system alone. This system can work as a passive system when there is a power failure due to a strong earthquake. Similarly, it uses the advantage of an active control system by enhancing the performance of a passive control system. Also, this system requires less energy compared to an active vibration control system.

Hybrid vibration control system can be used as hybrid base isolation system or as a hybrid mass damper. The hybrid base isolation system is the combination of an active device and base isolation, whereas the hybrid mass dampers (HMD) combine passive tuned mass damper with an active actuator.

Kyobashi Seiwa Building (1989)

Riverside Sumida Central Tower (1994)

Figure 2.10. Examples of structures equipped with Active mass damper

The development of hybrid mass dampers can be found in a number of researches, this includes, an arch-shaped HMD developed for bridge tower construction, building response reduction and ship roll stabilization (Tanida et al. 1991), a V-shaped HMD, which is an extension of the arch-shaped HMD having an easily adjustable fundamental period (Koike et al. 1994), a multistep pendulum HMD (Yamazaki, Nagata & Abiru 1992), a structure equipped with a DUOX HMD to achieve high control efficiency with a small actuator force (Kobori 1996; Ohrui et al. 1994), etc.

The experimental verification has been conducted by many researchers and can be found in (Kelly, Leitmann & Soldatos 1987; Reinhorn & Riley 1994; Reinhorn, Soong & Wen 1987; Yoshida, Kang & Kim 1994). The combination of an active vibration control device with a base isolator installed in the structure improves the performance of the system in terms of reducing the absolute acceleration and inters storey drift as the base isolator alone needs a large absolute base displacement. As a result, it is possible to reduce the inter-storey drift and maximum base displacement by adding an active vibration control device to form a combined system.

Spencer (Spencer Jr 2002) analysed the effectiveness of a smart base isolation system using MR damper numerically. Later, experimental verification were conducted on a base isolated two degree of freedom building model at the Structural dynamics and Control/Earthquake engineering laboratory at the University of Notre Dame. Laminated rubber bearings were used as a base isolation system. The experimental set up is demonstrated in figure 2.12. An

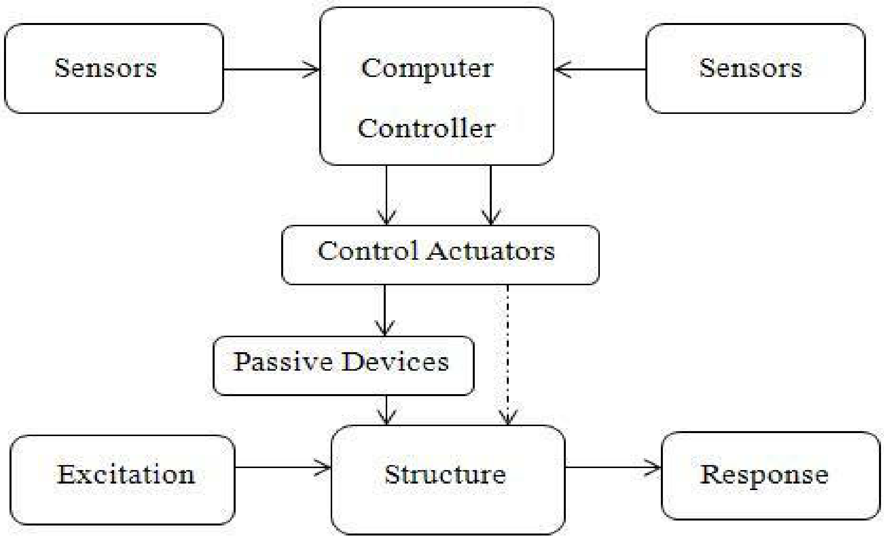


Figure 2.11. Hybrid vibration control system diagram

MR damper is used to control the structural response and installed between the base of the structure and the shake table. The control algorithm applied in this system to control the structural response was clipped optimal control. The results showed that implementation of MR dampers reduce the higher structural response to a great extent in comparison to the passive base isolation system. Accordingly, the effectiveness of a smart base isolation system was concluded.

Figure 2.10 shows the application of HMD in the real world structures. The 50 storey Yokohama landmark tower, completed in1993, and 52 storey Shinjuku park tower, completed in1994, are examples of HMD where the former one is equipped with two multi-step pendulum HMDs and latter one contains three V-shaped HMDs. Another example of this system is the 7 storey Kansai International airport control tower located in Osaka, Japan which was completed in 1992.

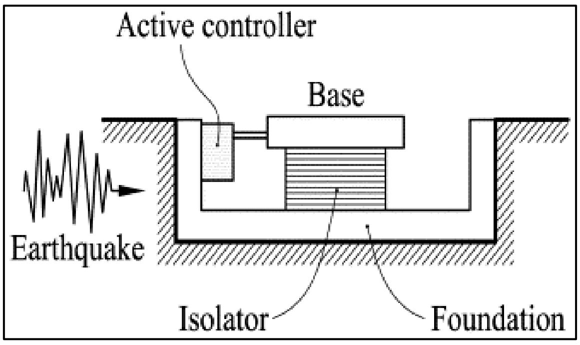


Figure 2.12. Experimental structure of the smart base isolation system

Yokohama Landmark Tower (1993)

Shinjuku Park Tower (1994)

Figure 2.13. Examples of structures equipped with Hybrid mass damper

Canton tower, as shown in figure 2.14, is a landmark of the city centre business area of China, with a total height of 600 meters, completed in 2010. It houses a restaurant, observatory and telecommunications facilities. The main tower is 454 meters tall with a 146 meter tall antenna on top. The HMD is composed of a passive tuned mass damper with two-stage damping level, and a compact active mass damper, which is driven by linear induction motors mounted on the tuned mass damper. In case of a failure in HMD control system, the system would become a passive TMD.

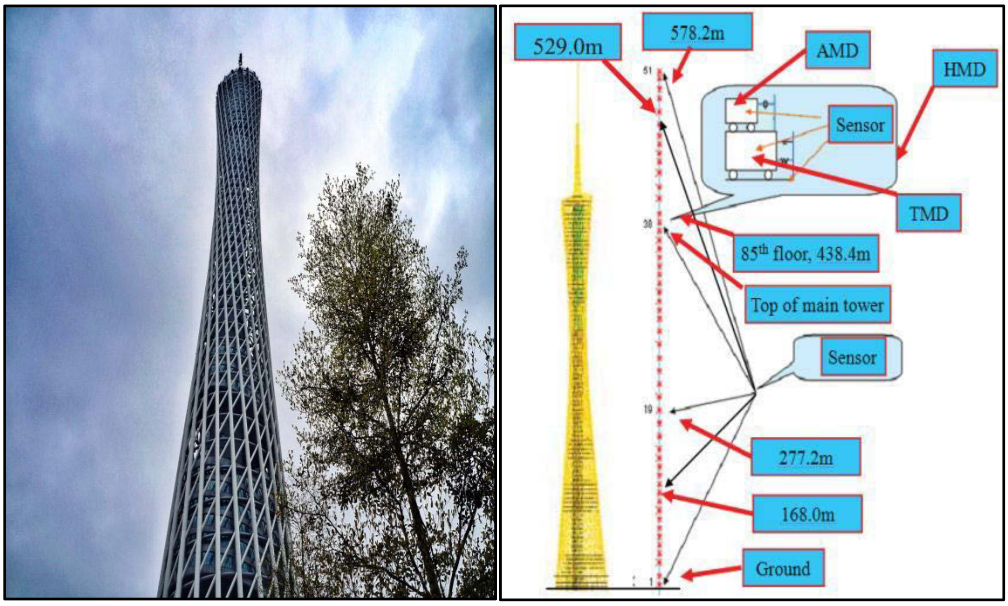


Figure 2.14. Canton tower in Guangzhou, China, completed in 2010

2.5. Semi-active vibration control devices

Semi-active vibration control system combines the best features of passive and active vibration control system and received a great deal of attention due to its adaptability of active device with low external power supply. These vibration control devices are very stable due to the fact that they are not capable of increasing the mechanical energy of the structural system and can be varied dynamically. Additional advantages include the less consumption of operating power and mechanical simplicity.

Figure 2.15 presents the schematic diagram of a semi-active vibration control system. The similarity in the basic configuration between this system and active vibration control system is noticeable. However, the uniqueness of this system is due to the presence of the features of both passive and active control system. Hence, they are known as controllable passive dampers. In general, the control forces are regulated using the feedback control system in the semi active control system. The control algorithm for this system can be adopted directly from any algorithm related to the active vibration control system by adjusting the maximum capacity of control device. Some common examples of control algorithm related to active control devices are bang-bang control (McClamroch & Gavin 1995; Mulcai, Tachibana & Inoue 1994) , clipped-optimal control (Dyke, Spencer Jr, Sain, et al. 1996c; Patten, He, et al. 1994; Patten, Kuo, et al. 1994) , resetting control (Yang 1999b, 2000b-a; Yang, Agrawal

&Kim 1999; Yang, Kim & Agrawal 2000), sliding mode control (Yang, Wu & Li 1996), and fuzzy logic control methods (Choi et al. 2004), etc.

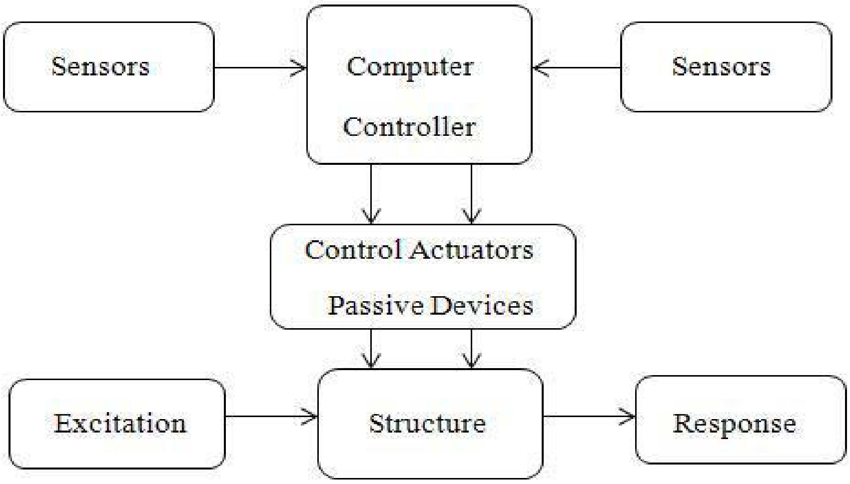


Figure 2.15.Typical schematic diagram of Semi-active vibration control system

Spencer Jr and Nagarajaiah (Spencer Jr & Nagarajaiah 2003) reviewed the developments and full scale implementations of semi-active vibration control system in the structures. There are different types of semi-active devices are available, such as variable orifice damper, variable friction damper, and controllable tuned liquid damper and controllable fluid damper. A brief explanation of these types will be discussed here.

2.5.1. Variable orifice damper

Due to the presence of controllable electromechanical variable orifice valve, this damper provides a wide range of damping levels. Figure 2.16 depicts the schematic diagram of the variable orifice damper. In order to obtain the required amount of damping, variable orifice valve controls the flow resistance of the hydraulic fluid inside the cylinder as shown in the figure.

The primary application of variable orifice damper was for controlling the motion of the bridges subjected to earthquake load (Feng & Shinozuka 1990; Kawashima, Unjoh & Shimizu 1992; Shinozuka, Constantinou & Ghanem 1992). A full scale investigation to determine the applicability and efficiency of a semi active vibration absorber for bridges was conducted at the University of Oklahoma Fears structural engineering laboratory. The device consists of a controllable orifice with a hydraulic actuator. Clipped-optimal control algorithm was used to determine the required control actions. The conclusion of the experimental test reported that a reduction of 65 – 70% in peak amplitude can be achieved by using this system (Patten, He, et al. 1994; Patten, Kuo, et al. 1994; Sack & Patten 1994; Varadarajan & Nagarajaiah 2004; Wongprasert & Symans 2005). The numerical simulation and experimental studies have been conducted to demonstrate the performance of variable orifice damper to mitigate the excitation of a building under seismic load (Hrovat, Barak & Rabins 1983; Mizuno et al. 1992).

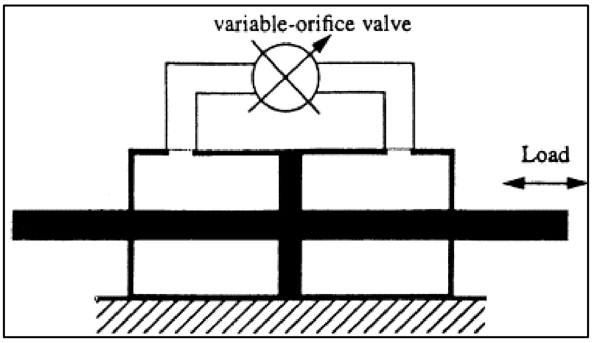


Figure 2.16. Schematic diagram of Variable orifice damper

Both the analytical and experimental researches were carried out for the development of active variable damping system (Kurata 1994, 1996). The component of this control device comprised of a variable hydraulic damper and a damping force controller. The latter one consists of a piston, a double rod cylinder and a flow control valve that controlled the opening level of the valve. The required damping force was controlled by the opening of the flow control valve. The power consumed by this control device was 30 watts and velocity sensors and a control computer were attached with the device. The control algorithm used for this device was the velocity feedback control based on optimal control. The investigation showed that the generation of required damping force with this control device was very close to the control force command. Besides, the reduction of the structural response of the active variable damping system was significantly satisfactory.

In the real world, the use of semi-active hydraulic damper can be observed where the variation of the opening rate of the control valve controls the damping force (Kurata 2001; Kurata et al. 2000; Kurata et al. 1998; Matsunaga 1998). A full scale installation of a semi active hydraulic damper took place at Kajima, Japan in 1998, as depicted in figure 2.17. Kajima Shizoka is an office building where the installed semi-active vibration control device can produce a maximum damping force of 1000kN using an electric power of 70 watts. To measure the response of the building, velocity sensors were used in the control system. The minimization of the structural response is obtained by determining the required damping. The control computers are programmed to command the damper to generate the necessary damping force. Also, effective and continuous operation was ensured by installing a power supply unit in case of power shut down due to an earthquake. The control algorithm used in

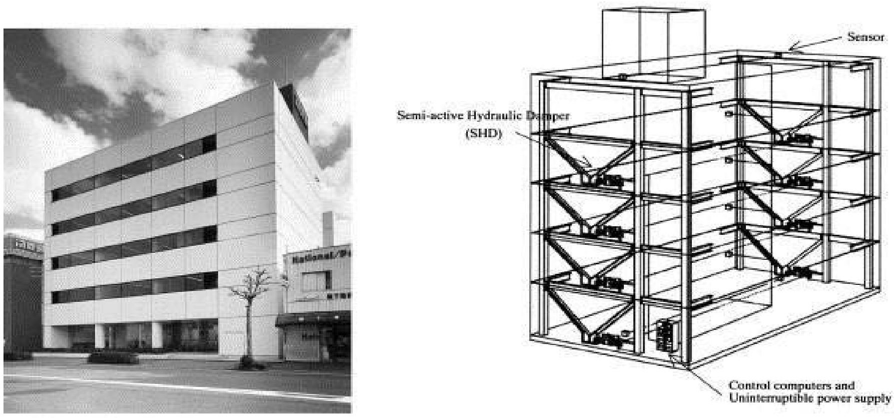


Figure 2.17. Kajima Shizuoka Building constructed with semi-active hydraulic dampers

the building is linear quadratic regulator which is based on relative and absolute velocity feedback. The results ensured an effective reduction in structural response of the structure with this semi-active damper.

In some research, active variable stiffness systems have been considered as seismic response control systems (Kamagata & Kobori 1994; Kobori & Kamagata 1992; Kobori et al. 1993; Nasu et al. 1996).This system controls the structural characterises of a building, such as stiffness, by mitigating the structural response when subjected to external excitations. In these works, variable stiffness devices (VSD) were installed between the intersection of braced frames and beams which ensures the flexibility of the connections. The required adjustable stiffness of the building to withstand the external excitation was achieved by VSD. This device can lock and unlock the connection between the frame and beams to employ the flexibility of the joint and thus, the required stiffness can be attained. Figure 2.18 shows the schematic diagram of VSD. Feed-forward control algorithm was used to determine the input motion to estimate the future structural response. After that, the structural stiffness was altered according to the predicted response. A comparison between an active variable stiffness system and semi-active continuous and independent variable stiffness system were examined by Spencer Jr and Nagarajaiah (Spencer Jr & Nagarajaiah 2003), and a considerable alteration of system stiffness was detected in the former system in comparison with the latter one.

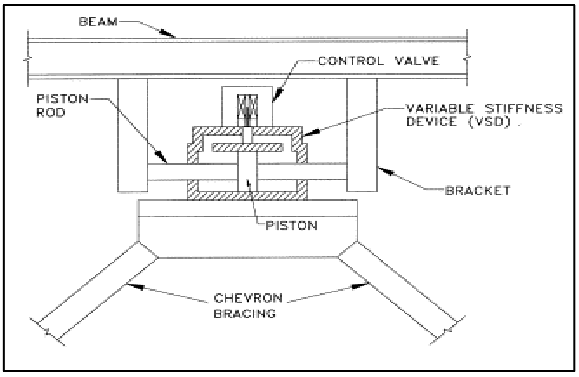


Figure 2.18.Schematic diagram of Variable Stiffness Device

Yang (Yang, Wu & Li 1996) has introduced the theory of sliding mode to control seismic excited buildings using an active variable stiffness systems. An effective control of stiffness and damping can be achieved by this theory in a dynamic system. The controller is designed to drive the response trajectory into the sliding surface where the response will be in an equilibrium position. The verification of this controller is demonstrated by numerical modelling of a three and eight storey building. The results indicate the robustness and effectiveness of the proposed system in terms of the reduction of the inter-storey drifts. Nevertheless, an increase in floor acceleration may be observed based on the seismic load and structural design.

Another type of semi-active control system is semi-active stiffness damper (SASD) which is developed analytically to reduce the structural response under dynamic loads (Yang 1999b, 2000b-a; Yang, Agrawal & Kim 1999; Yang, Kim & Agrawal 2000). This control device is a specific kind of hydraulic damper that comprises of a cylinder-piston system with a control valve in the bypass pipe which connects two sides of the cylinder. In this controller, the required damping is provided in the building by switching the control valve off/open and on/closed. The adopted control algorithm in this system is based on Lyapunov method and known as resetting control. In order to verify the effectiveness of this algorithm, a comparison was carried out with the switching control algorithm. The results ensured the functionality of SASD with respect to the reduction of the structural system under earthquake. Nonetheless, the effectiveness of different algorithms is earthquake-dependent and hence, the type of earthquake excitation should be taken into account for developing an efficient control algorithm to ensure the robustness of the system.

2.5.2. Variable friction damper

Variable friction damper is another type of semi-active device and the research on this device can be found in (Akbay & Aktan 1991; Akbay & Aktan 1990). The idea behind this damper is to dissipate energy from a structural system through surface friction. Figure 2.19 illustrates the schematic diagram of the variable friction damper. There are different types of variable friction damper; this one consists of a friction shaft that is installed at the bracing of the structure. The force generated at the frictional interface is adjusted by allowing slippage in a controlled amount. Investigation were conducted to determine the functionality of the damper using a one-storey model and a 20 storey building (Nishitani & Nittta 2001). The slip force level is controlled to exhibit a hysteresis with a constant ductility factor. Stammers and Sireteanu (Stammers & Sireteanu 2000) reported up to 50% reduction of structural response in comparison to the passive case using a semi-active friction damper.

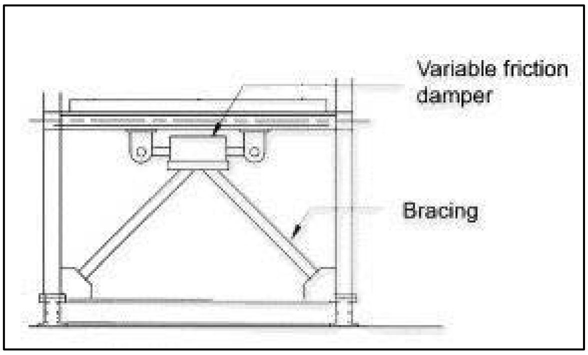


Figure 2.19. Schematic diagram of Variable friction damper

Developments of different control algorithm are reported by different researchers to enhance the performance of a damper in term of energy dissipation. Dowdell and Cherry (Dowdell &Cherry 1994) proposed two semi-active control algorithms, a variable slip force semi active friction damper and an alternative damper utilizing simplified 'off-on' control algorithm. The slip force is variable in these algorithms with respect to the structural response in order to reduce the RMS inter-storey drift. The performance of these proposed algorithms is compared with the constant slip force friction damper and a fully active tendon system.

Dupont and Stokes (Dupont & Stokes 1995) developed a simple bang-bang control algorithm for friction dampers. This control algorithm improves the effectiveness of friction dampers by increasing the energy dissipation in an instantaneous sense. The modulation of the normal force can be seen at the friction interface, whereas the induction of friction dynamic resulted is due to the effect of displacement and velocity. Both numerical and experimental studies confirm the performance of the proposed control system.

2.5.3. Controllable tuned liquid damper

Controllable tuned liquid damper is another example of semi-active device which improves the performance of passive devices, such as tuned liquid damper (TLD) or tuned liquid column damper (TLCD). A TLD can be considered similar to TMD in which liquid is used instead of mass. Similarly, A TLCD is one type of TLD which benefits from the motion of the liquid column in a U shaped tube to decrease the structural response. Since the passive vibration control devices are highly dependent on the type of excitation, the required damping may not be possible to control. However, the efficiency of the system can be improved by reducing the structural response when upgrading the device to a semi-active vibration controller (Kareem 1994; Yeh 1996a). TLD can also be improved by altering the length of the sloshing tank which will change the natural frequency of the liquid damper (Lou, Lutes & Li 1994). Haroun et.al (Haroun, Pires & Won 1994) reported the usage of a semi-active device based on a TLCD by introducing variable orifice.

Yalla and Kareem investigated the process of controllable tuned dampers and reported the method of achieving optimum amount of damping in the TLCD. Two optimal absorber parameters, the frequency range and damping ratio, of each damper needs to be determined first, and the desired damping level can be attained with the adjustment of the head-loss coefficient by controlling the orifice opening ratio.

For the semi-active tuned liquid dampers, different control algorithms can be found in the literature. These algorithms are applied for this system and are compared with passive systems. Three types of control strategies are numerically analysed by Yalla et al. (Yalla, Kareem & Kantor 2001) and demonstrated in figure 2.20. The model, as shown in the figure, was a multi-degree of freedom system combined with a TLCD, and three strategies are fuzzy logic control, full state feedback and observer-based feedback. It was reported that these semi-active strategies provide better performance in terms of reducing the structural response in comparison to passive systems. Also, the power required to operate the system is negligible and therefore the power of a battery can be used for the operation of the control valve. The on-off and continuously varying control algorithms were also applied to the system, and a comparison between these two algorithms showed that relatively simple on-off algorithm has a better performance than the continuously varying control system in order to reduce the structural response.

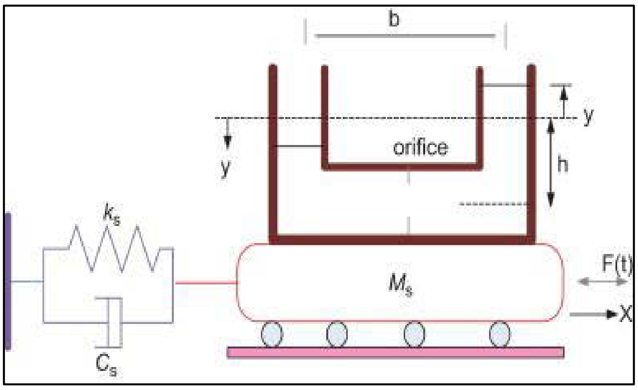


Figure 2.20. Semi-active TLCD system

2.5.4. Controllable fluid damper

Controllable fluid damper is also a type of semi-active device that dissipates the energy of an external excitation by means of controlling fluids. Unlike other semi-active devices, controllable fluid dampers do not have any electrically controlled valves or mechanisms; they only have a piston. Due to the simple configuration, this device is easy to maintain, yet reliable. A schematic diagram of this damper is shown in figure 2.21.

Controllable fluid dampers can be developed using two types of fluids, electro rheological (ER) fluids and magneto rheological (MR) fluids. The properties of these fluids are controllable as they can reversibly change from a free-flowing linear viscous fluid to a semi-solid. Therefore, the required yield strength can be obtained simultaneously whilst they are exposed to an electric field (for ER fluids) or magnetic field (for MR fluids).

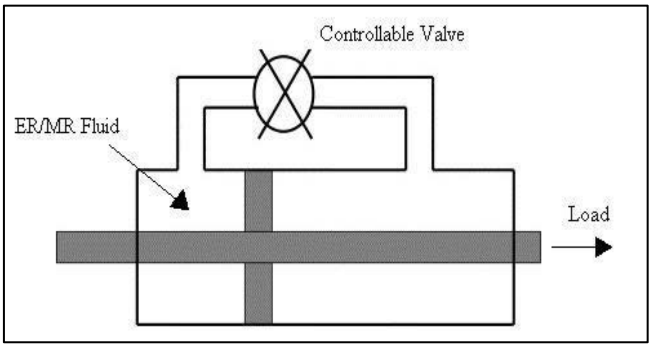


Figure 2.21. Schematic diagram of Controllable fluid damper

Several researches have been carried out for the development, modelling and testing of ER fluid dampers to investigate the vibration control for civil structures (Ehrgott & Masri 1994; Gavin, Hose & Hanson 1994; Leitmann & Reithmeier 1993; Makris et al. 1995; McClamroch & Gavin 1995; Rav 1994; Xu, Qu & Ko 2000). The model used by Burton et al. and Markis et al. (Burton et al. 1996; Makris et al. 1996)for ER fluid damper is presented in figure 2.22. The physical configuration of this damper contains an outer cylinder and a double-ended piston rod that pushes the ER fluid through a stationary annular duct. The created electric field is normal to the fluid flow. To implement the semi-active ER damper in the civil structure, modelling the response of this damper has been investigated. Sims et al. (Sims et al. 2000) presented a new modelling technique for semi-active ER dampers and also verified it through experimental tests. This model consisted of spring, mass and damper which were connected in series. Fluid bulk modulus and mass can be determined from the spring stiffness and fluid density, respectively. The damping characteristic was estimated by modifying a non-dimensional Bingham plastic function. Some key benefits of this model are the capability of predicting observed response and the suitability of using the algebraic sum for the control system.

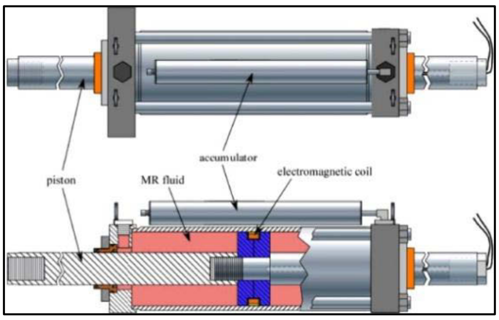


Figure 2.22. Proposed Electro rheological fluid damper

As mentioned earlier, MR fluid damper is also a controllable fluid damper used for vibration control in structures subjected to external loads (Carlson, Catanzarite & St. Clair 1996; Carlson & Spencer Jr 1996; Dyke & Spencer Jr 1996, 1997; Dyke, Spencer Jr, Sain, et al. 1996a, 1996b, 1996c; Dyke et al. 1997; Jansen & Dyke 2000; Ohtori et al. 2004; Spencer Jr & Dyke 1996; Yoshida & Dyke 2004). MR fluids are more beneficial than ER fluids in terms of predicting seismic response and thus, have a good potential to ensure safety under any seismic event. The first advantage of MR fluids over ER fluids is its ability to provide higher yield stress which makes them capable of generating large forces. Secondly, MR fluids are insensitive to contaminants or impurities occurring during manufacture and usage. Besides, they can be operated using batteries due to its lower power consumption. It requires less than 50 watts of power, approximately 12 to 24 volts of voltage and current driven power supply outputting only ~ 1- 2 amps.

The development of phenomenological models of MR dampers was conducted to predict the behaviour of MR dampers by researchers (Choi, Lee & Park 2001; Spencer et al. 1996; Spencer et al. 1997; Yang et al. 2002). The model used in these researches is the modified Bouc-Wen model which is an extension of the Bingham model.

LORD corporation investigated the applicability and efficiency of MR dampers by designing a full-scale 20 ton MR damper and installed in the real structure (Spencer Jr et al. 1997; Spencer Jr et al. 1998; Yang 2001; Yang, Jung & Spencer Jr ; Yang 2000b-b) as illustrated in figure 2.23. To build the damper, an outer cylindrical housing is used which is a part of magnetic circuit. In addition, two shafts are attached on both ends to support the damper. The final configuration of the damper consists of an inside diameter of 20.3cm with a stroke of ± 8 cm, 1m in length and a mass of 250 kg with 5 litres of MR fluid.

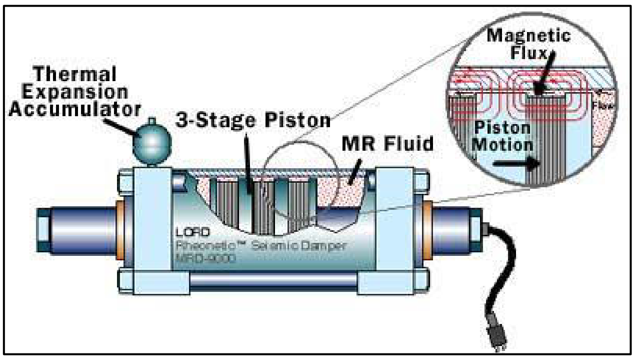


Figure 2.23. Schematic of the full-scale 20ton MR fluid damper

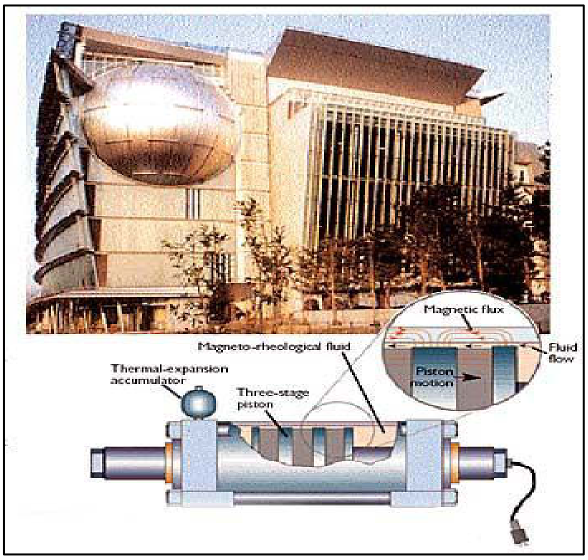


Figure 2.24. Tokyo National Museum installed with 30-t MR fluid dampers

In 2001, the Tokyo national museum of emerging science and innovation applied these dampers. This building is equipped with two 30 ton MR fluid dampers which are installed between the third and fifth floor as depicted in figure 2.24. The MR fluid built used in this building was manufactured by Lord corporation (Spencer Jr & Nagarajaiah 2003).

The first application of MR dampers in actual bridge structures was applied in a cable-stay bridge (Dongting Lake Bridge in China). This bridge consists of long steel cables which are subjected to vibration caused by the bridge itself or different weather conditions. For example, wind combined with rain that may cause cable galloping. Two LORD SD-1005 MR dampers are installed on each cable to reduce the vibration of the cable as demonstrated in figure 2.25.

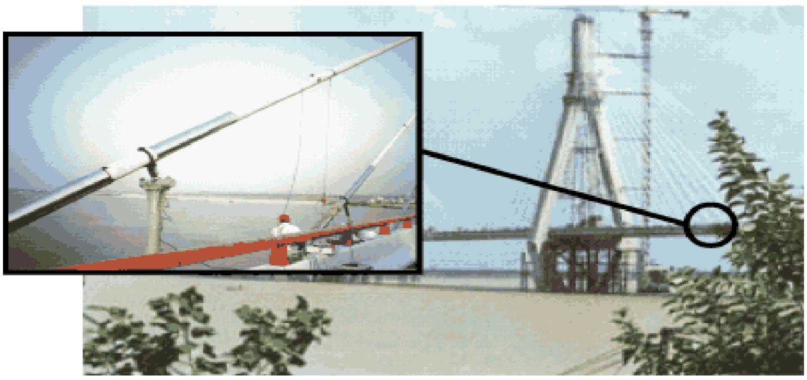


Figure 2.25. MR damper installed on Dongting Lake Bridge, China

Magnetorheological (MR) dampers are capable of offering the adaptability of active devices and stability and reliability of passive devices. One of the challenges in the application of the MR dampers is to develop an effective control strategy that can fully exploit the capabilities of the MR dampers. Bitaraf et al (Maryam Bitaraf, 2010) proposed two semi-active control methods for seismic protection of structures using MR dampers. The first method is the Simple Adaptive Control method which is classified as a direct adaptive control method. By using this method, the controlled system is forced to track the response of the system with desired behaviour. The controller developed using this method can deal with the changes that occur in the characteristics of the structure because it can modify its parameters during the control procedure. The second controller is developed using a genetic-based fuzzy control method. In particular, a fuzzy logic controller whose rule base determined by a multi-objective genetic algorithm is designed to determine the command voltage of MR dampers. In order to evaluate the effectiveness of the proposed methods, the performances of semi-active controllers were compared with some other control algorithms. Results revealed that the developed controllers can effectively control both displacement and acceleration response of the considered structure.

Another study discusses the modelling and application of MR dampers in semi-adaptive structures (A. Dominguez, 2008), as these fluids possess mechanical simplicity, high dynamic range, lower power requirements, large force capacity, robustness and safe manner operation in case of structural failure. A nonlinear new model based on the Bouc-Wen model, is employed to simulate the hysteresis behaviour of the damper. The model considers the frequency, amplitude and current excitation as dependent variables. The finite element model (FEM) of the MR damper element has also been developed based on the proposed model. Subsequently finite element of the adaptive structure embedded with MR dampers has been established and the nonlinear response of the whole structure is obtained.

In another study, the effectiveness of various seismic control devices for interconnecting two adjacent buildings for earthquake hazard mitigation has been investigated (S.D. Bharti, 2010). The effectiveness is examined for seismic response mitigation of adjacent multi story buildings under coupled building control scheme, involving passive-off, passive-on and semi active control strategies. In addition, the influence of damper location and maximum command voltage, on control performance has been examined.

The different types of vibration control devices considering their advantages and limitations have been discussed so far. In the next section, a brief introduction of MR fluids and devices is presented.

2.6. MR fluids and devices

Passive vibration control devices absorb the vibration energy subjected on the structure by external excitation. Active vibration control devices, on the other hand, need a significant amount of external power supply to be capable of producing control forces to neutralise the destructive energy of the external excitation. Semi-active vibration control devices advantage of the features of both passive and active vibration control devices. Therefore, when the external excitation is subjected and there is a power failure where the active control devices are not functioning, the passive control devices can compromise for it and reduce the vibrations subjected on the structure with their mechanical characteristics. Magneto Rheological (MR) dampers are typical examples of semi-active vibration control devices as they are highly efficient in the vibration reduction in addition to requiring subtle amounts of electricity which can easily be provided by batteries. MR fluids are typical examples of controllable fluids. These fluids were discovered in the late 1940s by Rabinow (Rabinow 1948, 1951). There exists micron-sized magnetisable particles suspended in a carrier liquid which when a magnetic field is applied, these particles align in the direction of the magnetic field giving the liquid the capability of transforming from a free-flowing viscous fluid to a semi-solid in milliseconds, as shown in figure 2.26. The reaction of the MR fluid due to a magnetic field is shown in figure 2.27.

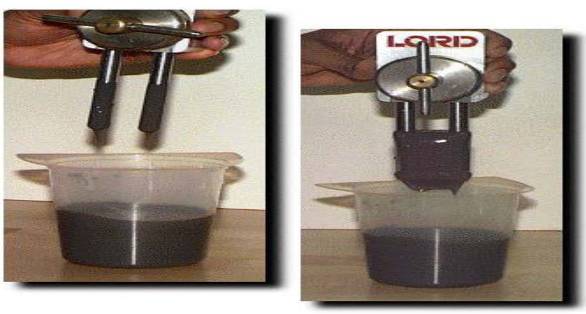


Figure 2.26. MR Fluid without (left) and with magnetic field (right)

MR fluids have 20 to 40% of their volume consisting of carbonyl iron particles which are only 3 to 5 micrometres in diameter. The particles are suspended in non-magnetic fluids like hydrocarbon oil or silicon oil. The strength of an MR fluid is a measure of the saturation magnetisation of the iron particles it consists of. As the saturation magnetisation of these particles increases, the MR fluid has stronger magnetic capacity. Experimental tests indicate the most efficient saturation magnetisation of iron particles to be 2.4 Tesla. Therefore, producing such particles is not cost-effective. In practical assumptions, the saturation magnetisation of iron particles is assumed to be 2.15 Tesla.

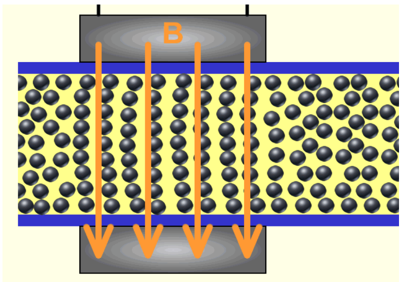


Figure 2.27.MR Fluid when a magnetic field is applied

MR fluids are manufactured by LORD Corporation. Table 2-1 compares the main characteristics of three types of controllable fluids used in MR fluids: MRF-240BS (water-based), MRF-132AD (hydrocarbon-based) and MRF-36AG (silicon-based). The characteristics of yield stress, magnetic field strength and magnetic induction of the LORD MRF-122-2ED are shown in figure 2.28 and figure 2.29.

Table 2-1.Characteristics of three different types of MR fluids (LORD Corporation)

MR FLUID	MRF-132AD	MRF-240BS	MRF-33AG
Base fluid	Hydrocarbon	Water	Silicone
Operating temperature (°C)	-40-130	0-70	-40-150
Density (g/cc)	3.09	3.818	3.45
Solids Weights (%)	81.64	83.54	82.02
Specific Heat@ 25°C	0.80	0.98	0.68
Thermal Conductivity (w/m°C)	0.25-1.06	0.83-3.68	0.20-1.88
Flash Point (°C)	>150	>93	>200

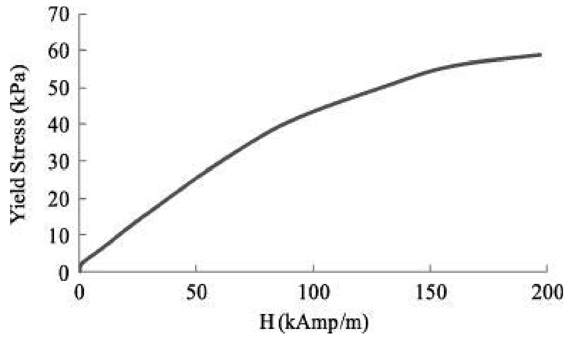


Figure 2.28. Yield stress vs. magnetic field strength of MRF-122-2ED (LORD Corporation)

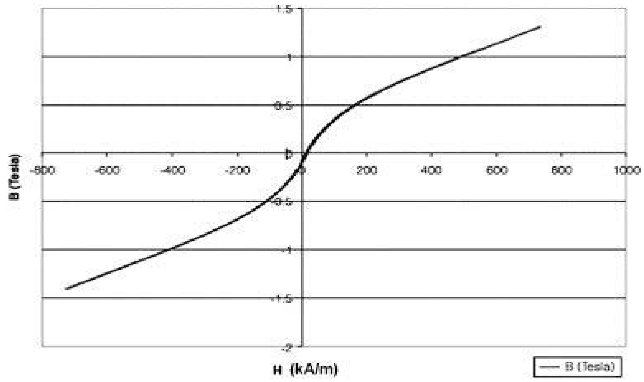


Figure 2.29. Magnetic properties of MRF-122-2ED (LORD Corporation)

2.7. Characteristics of MR fluids

The main characteristics of typical ER and MR fluids are presented in table 2-2. MR fluids are not very sensitive to the impurities it consists of which makes them easier to manufacture. In contrast to ER fluids, MR fluids are capable of operating in a broader range and with very low demanding voltage. In addition, the yield stress provided by MR fluids is greater than its ER counterparts. Since the iron is used as the solute, the density increases significantly in contrast to ER fluids. Even though both ER and MR fluids possess equal energy requirements, only MR fluids can easily function with very low voltage power (Carlson, Catanzarite & St. Clair 1996; Carlson 1996). MR devices are controllable with low voltage, current-driven power supply (1-2 amps) in contrast to ER devices which require a high voltage power source (~2000-5000 volts). In addition, this high voltage is capable of posing safety hazards. Table 2-2 provides the features of both fluids.

Table 2-2. Typical characteristics of ER and MR fluids (Carlson, Catanzarite & St. Clair 1996)

Property	**MR fluid**	**ER fluid**
Max. Yield Stress	50-100 kPa	2-5 kPa
Maximum Field	~250 kA/m	~4 kV/mm
Apparent Plastic Viscosity	0.1-10 Pa-s	0.1-10 Pa-s
Operable Temp. Range	-40-150°C	+10-90°C
Stability	Unaffected by most impurities	Cannot tolerate impurities
Density	3-4 g/cm3	1-2g/cm3
$\eta/\tau_y{}^2$	10-11-10-10 s/Pa	10-8-10-7 s/Pa
Maximum Energy Density	0.1 Joules/cm3	0.001 Joules/cm3
Power Supply(typical)	2-50V, 1-2A	2000-5000V, 1-10mA

2.8. MR devices and Applications

Devices consisting of MR fluids are categorised in three operating modes: (a) valve mode, (b) direct shear mode, or (c) squeeze mode, as shown in figure 2.30 (Butz & Von Stryk 2002; Yang 2001). The valve mode is a fixed-magnetic pole mode, mainly implemented in servo-valves, dampers and shock absorbers. The shear mode is used mainly in clutches, brakes and dampers. The squeeze mode, which is a combination of the valve and the direct shear mode, is mainly used in small amplitude vibration dampers.

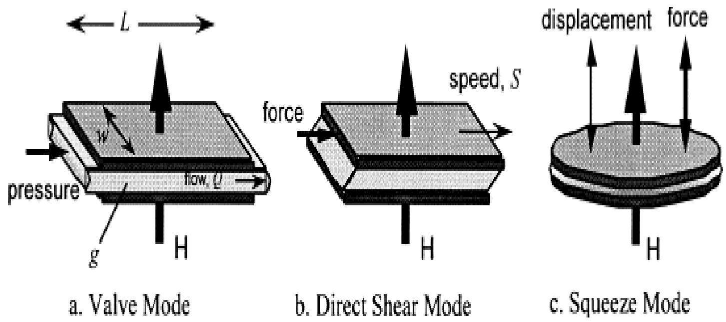


Figure 2.30. Three typical operating modes for MR fluid devices (Butz & Von Stryk 2002)

In actual structural implications, the required displacements and damping forces are very high in magnitude. Therefore, MR dampers operating with shear or squeeze mode are not applicable. Usually, valve mode combined with direct shear mode is taken into account. Typical examples of MR dampers are presented in the following section.

A small scale SD-1000 MR damper is produced by LORD Corporation (*Takenaka Corporation*; Carlson 1996; Dyke, Spencer Jr, Sain, et al. 1996b; Jolly, Bender & Carlson 1999) as shown in figure 2.31. MR fluids flow from a high pressure chamber to a low pressure chamber using an orifice located in the piston head. The main cylinder has a diameter of 3.8cm and the length of the damper exceeds to 21.5 cm. The main cylinder consists of the piston, the magnetic circuit, an accumulator, and 50 ml of MR fluid. A stroke of $\pm$2.5cm is provided by this damper.

A20 ton prototype large-scale MR fluid damper is manufactured in the LORD Corporation in collaboration with the Structural Dynamics and Earthquake Engineering Laboratory at the University of Notre Dame (Spencer Jr et al. 1998; Yang et al. 2002). The main feature of this damper is presented in table 2-3.

The magnetic field is perpendicular to the fluid flow which is provided by an electromagnet in the piston head. This damper is capable of producing forces of up to 3000 N.

Table 2-3. Characteristics of the 20ton MR damper

Stroke	$\pm$8cm
Maximum velocity	10 cm/s
Nominal cylinder bore	20.32 cm
Maximum input power	<50 watts
Normal maximum force	200,000N
Effective axial pole length	~5.5-8.5cm
Coils	~3$\times$1000turns
Maximum yield stress	~70kPa
Apparent fluid plastic viscosity	1.5 Pa-s
$\eta/{\tau_y}^2$	2×10^{-10}s/Pa
Gap	~1.5-2mm
Active fluid volume	~90 cm^3
Wire	16 gauge
Inductance	~6H
Resistance	~3$\times$7Ω

The most common type of MR dampers is the RD-1005-3 damper manufactured by LORD Corporation, as shown in figure 2.33. As a magnetic field is applied, this damper is highly efficient in controllability, energy density and responsiveness.

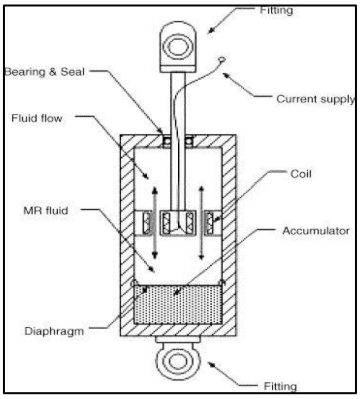


Figure 2.31. Small-scale SD-1000 MR Fluid damper (Yang 2001)

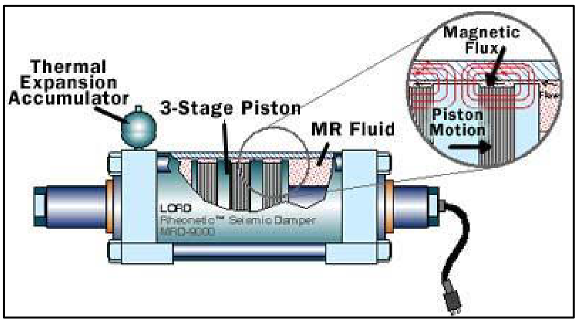


Figure 2.32. Large-scale 20ton MR Fluid damper (Yang 2001)

Figure 2.33. MR damper RD-1005-3

A variety of products manufactured by LORD Corporation with the rheonetic systems trademark exists. Some examples include:

- Automotive suspension devices

These devices improvised MR fluids instead of hydraulic shock absorbers. A controller is used for the damping features in real-time.

- MR passenger protection devices

These devices improvise MR fluids in airbag systems, seatbelts and the vehicle seats, therefore safety factors are guaranteed.

- Seismic Protection

Due to rapid time response and low power requirements, MR dampers are widely used in structures to mitigate the hazardous energy of the external excitations, as shown in figure 2.34 and 2.35.

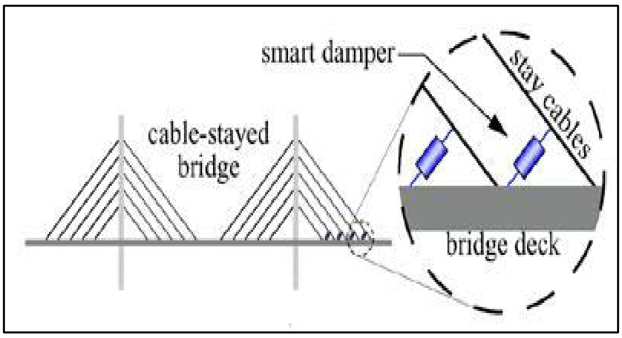


Figure 2.34.MR dampers installed in a bridge

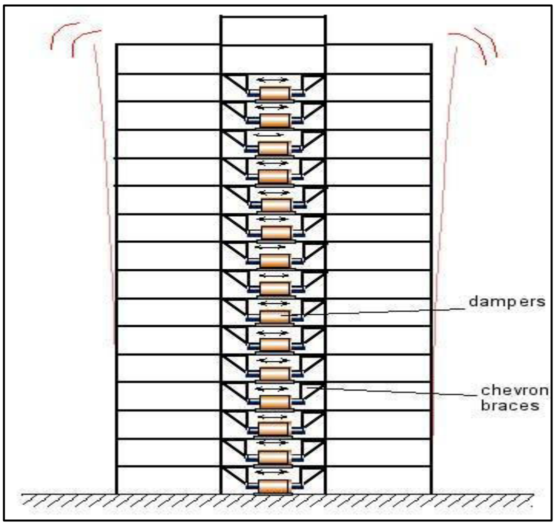


Figure 2.35. Examples of MR dampers installed in a building

- Washing machines

MR dampers manufactured by LORD Corporation are applied in washing machines and other electrical appliances to reduce the noise and vibrations produced in these devices, as shown in figure 2.36.

Figure 2.36.MR damper installed in a washing machine

- Prosthesis devices for amputated legs

These prosthesis devices are produced by a German firm (Biedermann OT Vertrieb) which improvised MR dampers in their device to improve stability and energy efficiency and also reduce the response time to milliseconds.

Figure 2.37.MR damper applied in lower leg prosthesis

- Vehicle seat suspension

This suspension is mainly used for buses and truck seats to enhance comfort. They have a better performance in comparison to air-suspension seats as they are adaptable to the varying weight of different drivers and the road oscillations, as shown in figure 2.38.

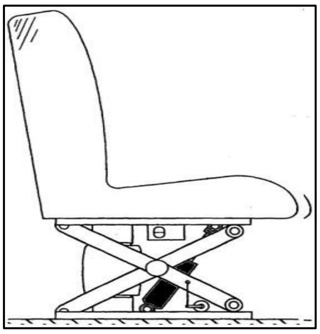


Figure 2.38. Heavy duty seat suspension with MR damper

2.9. MR damper modelling

Control algorithms that improvise the characteristics of MR dampers need to be developed. For the parameter identification and model evaluations, experimental data (displacement, velocity and damping forces) for various ranges of control currents and frequencies is required, as shown in figure 2.39.

Force versus velocity or force versus plots varies based on the control current. The forces versus displacement plots of MR damper pursues a clockwise path due to the increase in time in contrast to the forces versus velocity plot which pursues a counter-clockwise pace due to increase in time. The force versus velocity features of MR dampers are demonstrated by curves with considerable hysteresis for lower velocities (pre-yield) and linear force for higher velocities (post-yield). The current approaches zero when the smallest hysteresis indicates a viscous characteristic. As the control current increases, the damper force increases accordingly.

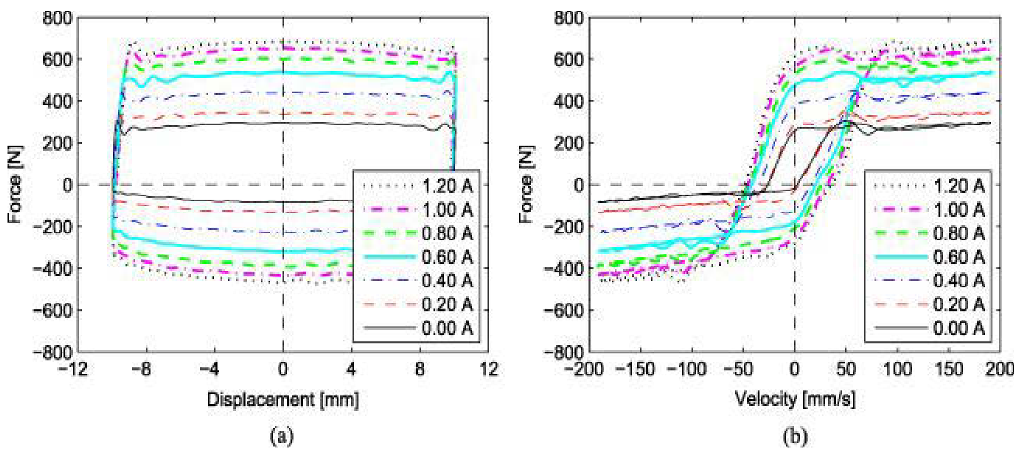


Figure 2.39.Characteristics of damper force for different currents provided: (a) non-linearly in force versus displacement and (b) hysteresis in force versus velocity

Various models known as quasi-static and dynamic models are established to take into account the non-linear and hysteresis characteristics of MR dampers (Lee & Wereley 2000; Wang & Gordaninejad 2000). These models are efficient for the force versus displacement behaviour of MR dampers whilst they have poor performance when modelling the nonlinear force versus velocity curve of the damper (Yang 2001). Therefore, these models are insufficient for the analysis and design of structural control algorithms.

To overcome this setback, dynamic models are proposed. Two classifications exist for dynamic models: a) non-parametric models and b) parametric models. The non-parametric model in which the performance of the MR damper through various experimental set ups is required. Good examples are Chebychev polynomials (Ehrgott & Masri 1992; Gavin 1996), neural networks (Chang & Roschke 1998; Wang & Liao 2001; Xia 2003; Zhang & Roschke 1998), and neuro-fuzzy systems (Schurter & Roschke 2000).

Parametric models improvise mechanical characteristics (mass, damping and stiffness) to provide the features of the device. These parametric models are presented below:

2.9.1. Bingham model

The stress-strain behaviour of MR fluids can be modelled by the Bingham model. As defined in this model, the MR damper has a solid behaviour until a minimum yield stress τ_y is surpassed and afterwards shows a linear behaviour for the stress and changes in shear$\dot{\gamma}$. Therefore, the shear stress τ for this fluid is presented below:

$$\tau = \tau_y(field)sgn(\gamma) + \eta\dot{\gamma}; \tag{2.1}$$

where τ_y(field) is the yield stress provided by the magnetic field and η is the fluid velocity.

According to the Bingham model, Stanway, Sproston and Stevens (Stanway, Sproston & Stevens 1985; Stanway, Sproston & Stevens 1987) established a mechanical model with the same name which includes a Coulomb frictional element with a dashpot in parallel to it, as shown in figure 2.36. Spencer (Spencer et al. 1997) used this model for a small MR fluid damper. The MR damper force is presented as:

$$f = f_c sgn(\dot{x}) + c_0\dot{x} + f_0; \tag{2.2}$$

where f is the damping force, f_c is the friction force, *sgn(.)* the signum function, $\dot{x}$ the velocity, x the displacement, c_0 the viscous coefficient and f_0 is the initial value for the damper force which is the mean produced by the accumulator.

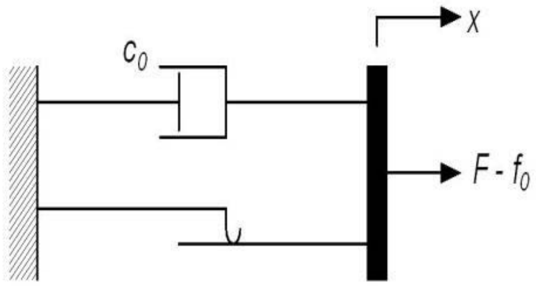


Figure 2.40. Bingham model for a fluid damper (Stanway, Sproston & Stevens 1985; Stanway, Sproston & Stevens 1987)

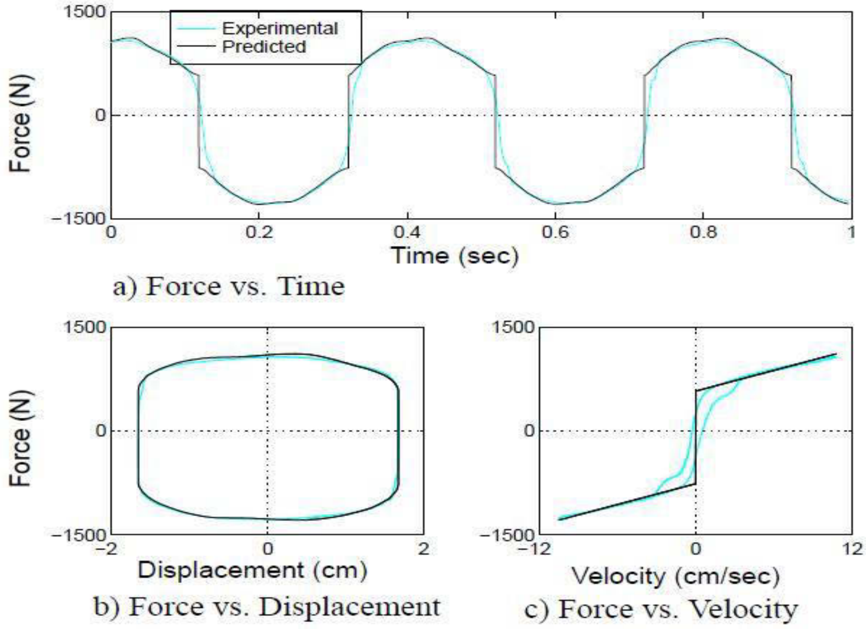


Figure 2.41. Verifying the Bingham model with the experimental results (Spencer et al. 1997)

As an implementation, this model is tested with a *2Hz* sinusoidal response function in which the voltage provided is *1.5V*. The model characteristics are: $f_c = 670N$, $c_0 = 50Ns/cm$, and $f_0 = -95N$. As illustrated in figure 2.41, even though the behaviour of the fluid is described well beyond the yield point, it does not define the behaviour of the damper in the vicinity of zero velocity in which the pre-yield region is encountered. This model is not efficient when defining the nonlinear force-velocity curve of the damper when the displacement and velocity have the same sign and small magnitude velocities are encountered. Therefore, this model is efficient when the response needs to be analysed.

The Bingham model is extended by Gamota and Filisko in 1991(Gamota & Filisko 1991). In which a solid model in series with the original Bingham model is considered, as shown in figure 2.42. The force in the damper is presented by the equations below:

$$f = k_1(x_2 - x_1) + c_1(\dot{x}_2 - \dot{x}_1) + f_0$$
$$= c_0\dot{x}_1 + f_c sgn(\dot{x}_1) + f_0$$
$$= k_2(x_3 - x_2) + f_0 |f| > f_c$$
$$f = k_1(x_2 - x_1) + c_1\dot{x}_2 + f_0$$
$$= k_2(x_3 - x_2) + f_0 |f| \leq f_c; \quad (2.3)$$

where k_1,k_2, and c_1 are the linear solid parameters and c_0 is the Bingham model damping coefficient.

The frequency and voltage are the same as the Bingham model in the previous section. The model parameters are $f_c = 650N, c_0 = 500Ns/cm, c_1 = 1300Ns/cm, k_1 = 5 \times 10^4 N/cm$, $k_2 = 2 \times \frac{10^6 N}{cm}$ and $f_0 = -95N$. The predicted response versus the experimental data is presented in figure 2.39. Based on this model, the force versus displacement of the MR damper is accurately verified by the experimental results. But the main setback of this model is not having the near zero velocity hysteresis relationship between the force and velocity of the MR damper. Therefore, when this model is used for numerical means very small simulation steps need to be defined (Spencer et al. 1997).

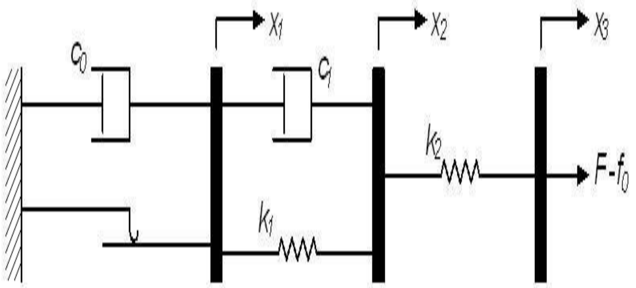


Figure 2.42. Extended Bingham model (Gamota & Filisko 1991)

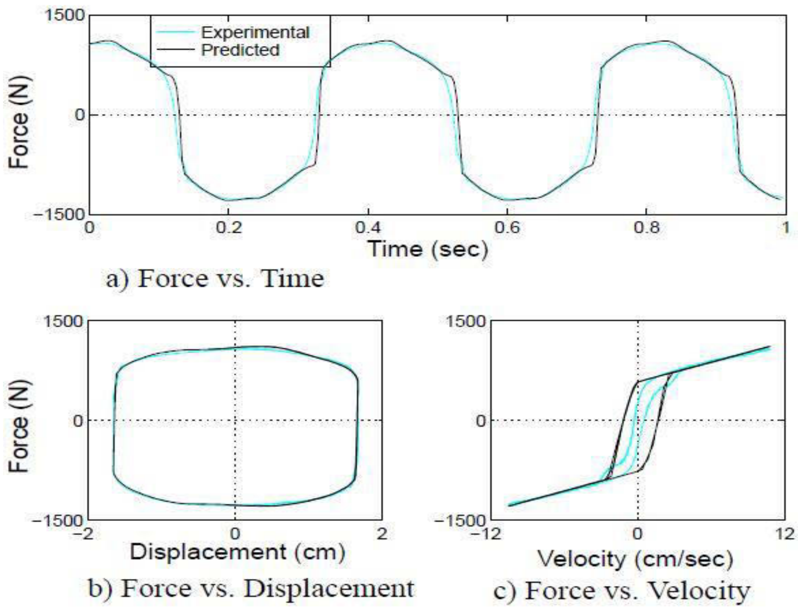


Figure 2.43. Verifying the Bingham model with the experimental results (Spencer et al. 1997)

2.9.2. Bouc-Wen model

The Bouc-Wen model was first proposed by Spencer (1997), as shown in figure 2.44. This method of verifying the response of the hysteresis system of the MR damper is similar to Wen (1976). The force produced by the MR damper is presented below:

$$f = c_0\dot{x} + k_0(x - x_0) + \alpha z; \tag{2.4}$$

where c_0 is the viscous coefficient, k_0 is the linear spring stiffness, x_0 is the initial displacement of the spring, α is the scaling coefficient in the yield stress of the MR fluid and z is an evolutionary variable defined by the equation below:

$$\dot{z} = -\gamma z|\dot{x}||z|^{n-1} - \beta\dot{x}|z|^n + \delta\dot{x}. \tag{2.5}$$

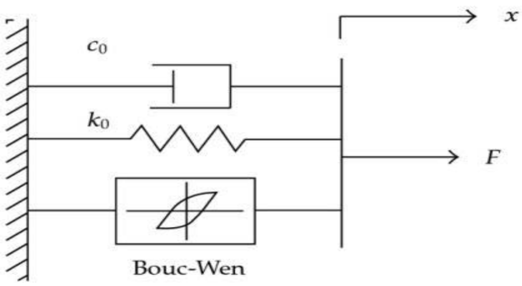


Figure 2.44. Bouc-Wen model of MR damper

The MR damper parameters are: $\alpha = 880N/cm$, $c_0 = 500Ns/cm$, $k_0 = 25N/cm$, $\gamma = 100cm^{-2}$, $\beta = 100cm^{-2}$, $n = 2$, $\delta = 120$ and $x_0 = 3.8cm$. A comparison between the predicted response and the experimental data is shown in figure 2.45. Even though this model is capable of defining the characteristics of MR dampers it is not capable of defining the force/velocity in the vicinity of small velocities (Spencer et al. 1997).

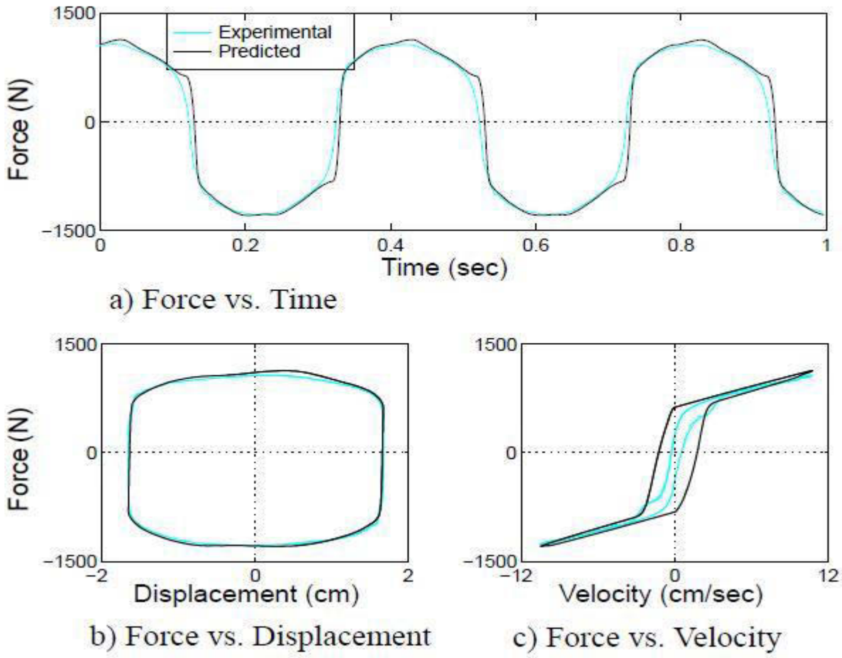


Figure 2.45. Verifying the Bouc Wen model with experimental results (Spencer et al. 1997)

2.9.3. Modified Bouc-Wen model

The modified Bouc-Wen model was first proposed by Spencer (1997) to capture the hysteresis behaviour of the MR damper, as shown in figure 2.46. The force equilibrium in this figure results in the equation below:

$$c_1\dot{y} = c_0(\dot{x} - \dot{y}) + k_0(x - y) + \alpha z; \tag{2.6}$$

in which the equation covering the evolutionary variable is presented below:

$$\dot{z} = -\gamma z|\dot{x} - \dot{y}||z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + \delta(\dot{x} - \dot{y}). \tag{2.7}$$

When the equation (2.6) is solved, the results are as below:

$$\dot{y} = \frac{1}{(c_0+c_1)}\{\alpha z + c_0\dot{x} + k_0(x - y)\} \tag{2.8}$$

$$f = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0). \tag{2.9}$$

The total force from equation (2.6) can be written as the form below:

$$f = c_1\dot{y} + k_1(x - x_0) \ . \tag{2.10}$$

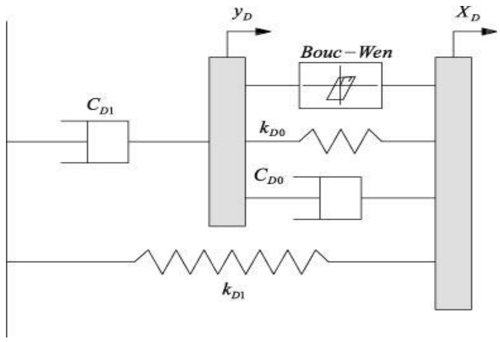


Figure 2.46. Modified Bouc-Wen model of MR damper (Spencer et al. 1997)

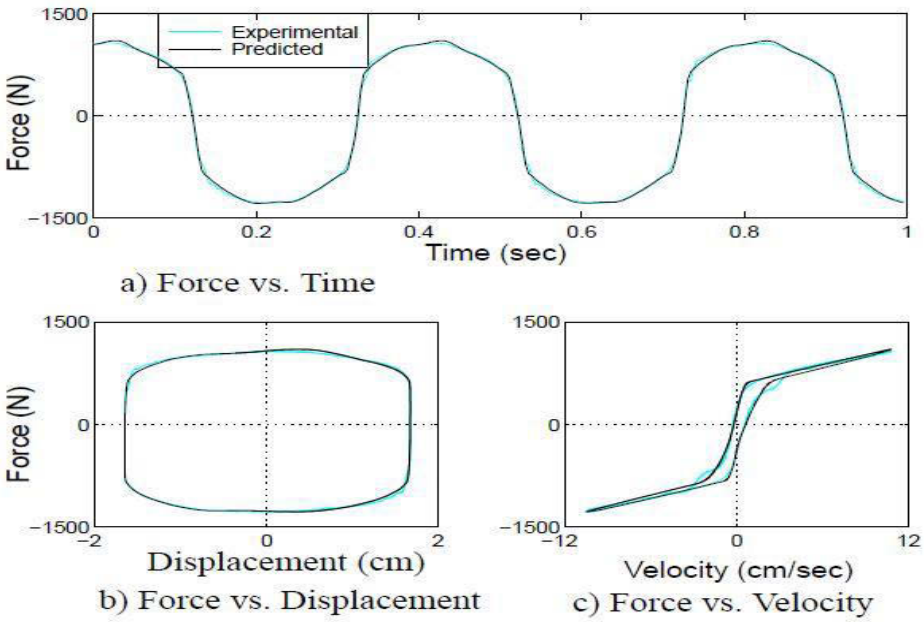


Figure 2.47. Verifying the Modified Bouc-Wen model with the experimental results (Spencer et al. 1997)

The parameters of the MR damper are:

$\alpha = 963N/cm, c_0 = 53Ns/cm, k_0 = 14N/cm, c_1 = 930Ns/cm, k_1 = 5.3N/cm,$
$\gamma = 200cm^{-2}, \beta = 200cm^{-2}, n = 2, \delta = 207$ and $x_0 = 18.9cm$.

The verification between the predicted response and the experimental data is shown in figure 2.47. As anticipated, this model is highly efficient in defining the damper behaviour in all regions (Spencer et al. 1997). The setbacks encountered in this model is it not being capable of modelling the non-symmetric hysteresis of the MR damper in addition to the differential equations presented in this model which can influence the system robustness.

2.9.4. Static hysteresis model of MR damper

This model defines the hysteretic force-velocity behaviour of the MR damper. The mechanical model is similar to the Bouc-Wen model, as shown in figure 2.48. In this model a hyperbolic tangent function is considered to model the hysteresis and the damper viscous and stiffness parameters. The equation considered for this model is presented below:

$$f(x) = c\dot{x} + kx + \alpha z + f_0 \tag{2.11}$$

$$z = \tanh(\beta\dot{x} + sgn(x)); \tag{2.12}$$

where c and k are the viscous and stiffness parameters, α is a hysteresis scale factor, z accounts for the hyperbolic tangent function which captures the hysteresis effect and f_0 is the damper force offset.

This simple hysteretic tangent function is efficient when computing the parameters of this damper when designing and implementing it in the structure.

The parameters used to capture the hysteresis effect of this model are illustrated in figure 2.49. This figure shows the force-velocity curve for the MR damper based on the variations of different parameters. The viscosity term $c\dot{x}$ is a line indicating the velocity versus damper force after the yielding point. If c is large, a steep inclination is observed in this line. The stiffness term k, is in charge of the *opening* in the hysteresis curve near the zero velocity region. If k is large, the opening is provoked to increase. Stiffness and damping are significant parameters for a damper without hysteresis effect.

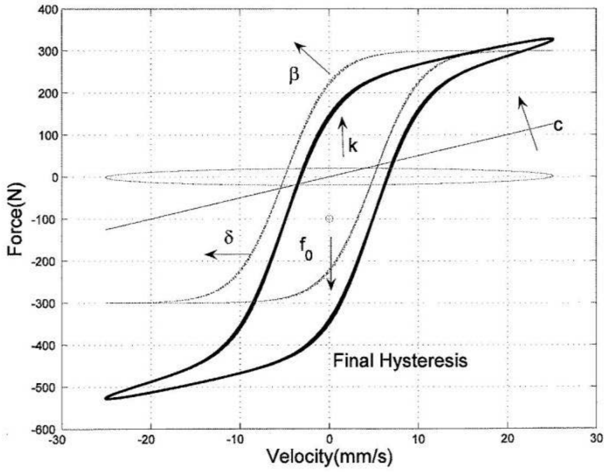


Figure 2.48. Hysteresis Parameters for Static hysteresis model of MR damper

As shown in figure 2.48, the initial hysteresis loop is smaller and is dependent on the scale factor of the damper velocity in the hysteresis curve β. In which, the larger value of β, the steeper the slope will be. The width of the hysteresis is dependent on $\delta sign(x)$; the sign function of the displacement and the scale factor δ. The height of the hysteresis is dependent on the coefficient α. The offset value f_0 shifts the initial hysteresis loop (Nguyen 2009).

To this point, MR fluids, their behaviour and the modelling formulas have been discussed. A setback encountered when applying MR fluids is its nonlinear characteristics. Therefore, the control algorithm that considers this nonlinearity is significant. The non-parametric models; Bouc-Wen and modified Bouc-Wen model, are efficient for modelling MR devices. However, these models do not consider the non-symmetric hysteresis in the force-velocity curve. Therefore, proposing a model of MR damper that can overcome this setback is a challenging task.

The control algorithms chosen is highly influential on the performance of a structural control system (Jung et al. 2006). In the following chapter, various control algorithms are discussed; Lyapunov based controller, linear quadratic regulator (LQG) control, fuzzy logic control and etc.

In this section, different control algorithms for MR dampers have been discussed. Brief information on the theory and design of Lyapunov-based control and linear quadratic regulator (LQR) has been provided. Furthermore, intelligent control (fuzzy logic control) has also been introduced and discussed.

2.10. Lyapunov Control

There are several structural control systems based on the Lyapunov stability method (Gavin 2001; Kuehn & Stalford 2000; Leitmann 1994; Wang & Gordaninejad 2002); in which a Lyapunov function $V(y)$ must be assumed. This function is required to be a positive definite function. Based on the Lyapunov stability method, the system is stable for an equilibrium point if the derivative of Lyapunov function is negative. In control theory, the Lyapunov function is of the form below:

$$V(y) = \frac{1}{2}||y||_P^2; \tag{2.13}$$

where $||y||_P$ is *P-norm* of the state variables as shown below:

$$||y||_P = [y^T P y]^{1/2}. \tag{2.14}$$

In equation (4.3), Q is a real, symmetric, positive-definite matrix. Therefore, to achieve stability in the system, the derivative of the Lyapunov function is required to be negative definite. If the system is linear, the matrix P is achieved when the Lyapunov equation is solved:

$$A_0^T P + P A_O = -Q_P. \tag{2.15}$$

where A_0 is the system matrix in the generic form of the state space equation and Q_P is assumed to be a positive definite matrix.

2.11. Linear quadratic regulator(LQR) control

Linear quadratic regulator (LQR) control is commonly used for semiactive vibration devices as it is simple and stable. The desired control force is achieved when the performance index below is minimised:

$$J = \int_0^\infty (y^T Q y + f^T R f) dt; \tag{2.16}$$

where the desired control function is achieved:

$$f_c = -\frac{1}{2} R^{-1} B_0^T P y = G y; \tag{2.17}$$

where A_0 is the system and B_0 is the input matrix in the generic form of the state space equations and Q is a given positive definite matrix, R is a given positive matrix, and P is a positive definite matrix when the Riccati equation is solved, as shown below:

$$PA_0 + A_0^T P - \frac{1}{2} PBR^{-1} B_0^T P + 2Q = 0. \tag{2.18}$$

when the desired control force is achieved, an inverse neural network is used to determine the voltage required for this force (Chang & Zhou 2002; Zhou, Chang & Spencer 2002).

2.12. Fuzzy Logic

Fuzzy logic was first introduced by Prof. Lotfi A. Zadeh, at University of California at Berkeley, in 1965.The concept of this theory imitates the process the human brain deals with uncertainty, vagueness and imprecision. In contrast to Boolean logic where an argument definitely belongs to or does not belong to a particular set, Fuzzy logic describes partial belonging to a particular fuzzy set. Therefore, the degree of membership of an argument to a fuzzy set is defined. Fuzzy sets could be defined as any linguistic variable such as "fast", "slow", "hot", "cold", etc.

In Boolean logic, for instance, if membership functions were to be defined for light, moderate and severe damage to the structure, 0 to 29% damage could be considered as light damage, 30 to 60% damage could be considered as moderate damage, and 61 to 100% could be known as severe damage, as shown in figure 2.49. Therefore, based on this linguistic categorisation, if a structure withholds 61 or 62% damage, it is considered to have encountered severe damages. In contrast to this classification, in fuzzy logic, degrees of membership functions are defined to describe the percentage of a particular variable to a fuzzy set. It allows variable to partially belong to a fuzzy set in addition to belonging to more than one set at the same time. Therefore, if fuzzy logic were used instead of Boolean logic for the damage example mentioned, fuzzy sets would be defined as shown in figure 2.50. Therefore, based on this definition, a structure that withholds 60% damage is categorised as having a membership degree of 0.3 in the severe damage set and 0.7 in the moderate damage set. On the other hand, if the structure had experienced 30% damage, the membership degree would be 0.7 in the moderate damage set and 0.3 in the light damage set. Therefore, as shown in this example, fuzzy logic, uses fuzzy systems and membership functions to imitate the thinking procedure of the human brain.

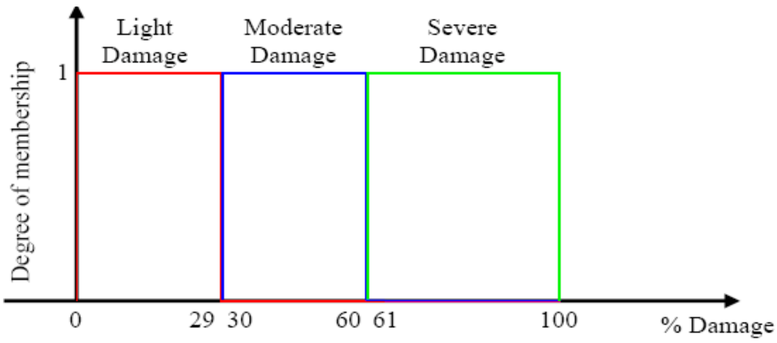


Figure 2.49. Boolean functions categorising structural damage

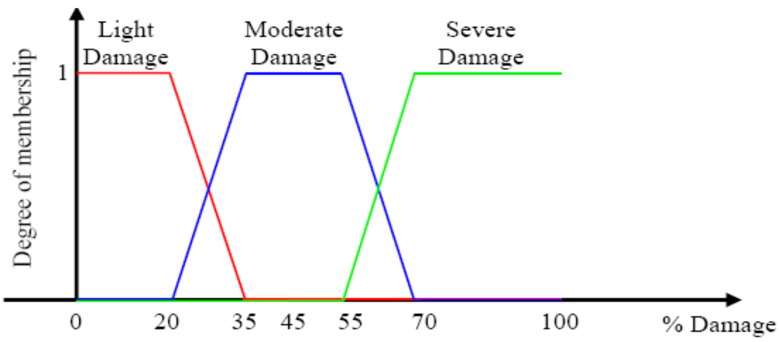


Figure 2.50. Fuzzy functions categorising structural damage

A very useful application of fuzzy logic in civil engineering is fuzzy logic control. In which, fuzzy rules are defined to determine the action that needs to be taken, based on the sensed response of the structure. Research has been conducted on their application in seismic vibration reduction of structures due to external excitations; active and semi-active control. This method is advantageous over other methods as it acquires simple algorithms, its suitable for real-time control, there is no requirement for information on the structural and vibration characteristics of the plant, the system is robust in terms of performance and implementation (Wong et al.1999)

Fuzzy logic control improvises expert knowledge instead of rigorous equations to describe the behaviour of a system. It uses fuzzy information to dictate desirable control actions and is used in complex systems in which there is no simple mathematical model, the system is highly nonlinear or there is ambiguity or vagueness in the system (Pacific Northwest National Laboratory and Batelle Memorial Institute 1997).

2.13. Fuzzy Logic Control for Structural Vibration Reduction

As mentioned above, fuzzy control consists of the rules in the format of IF...THEN statements, which relate the input variables to the desirable output, or control action. The procedure starts with defining membership functions for the inputs and outputs using linguistic terms. In structural control, the inputs are usually the sensed structural responses: displacement, velocity or acceleration. The crisp input values obtained from the sensors are assigned membership functions and degrees of membership. This step is known as the fuzzification step. The next step is the decision making step, in which predetermined rules are used to relate the fuzzy input values to fuzzy outputs. In the end, the output values are defuzzifed, in which they are converted into crisp values which can be used as control actions. The inference rules and the membership functions determine the effectiveness of the fuzzy logic controller.

Inactive seismic vibration control, fuzzy logic control is used to determine the desired control force to be applied to the actuator (Casciati et al.1994 a,b,c, Casciati and Yao 1994, Furuta et al. 1994, Iiba et al. 1994, Goto et al. 1994, Yamada et al. 1994, Yeh et al. 1994, Fujitani et al. 1995, Battaini et al. 1997, 1998, Aldawood et al. 2001, Mitsui et al. 2002)

In semi-active control, however, fuzzy logic is used to vary the mechanical properties of the device. It is applied to seismic vibration reduction bridges due to earthquakes or traffic loading with variable dampers (Sun and Goto 1994), or control of structural vibrations with hybrid systems consisting of base isolation and semi-active dampers (Nagarajaiah 1994, Symans and Kelly 1999, Wongpresert and Symans 2001).

2.14. Summary

In this chapter, a literature review of different types of vibration control devices has been discussed and recent achievements have been introduced. MR dampers and their applications have been analysed, therefore a background regarding the semi-active vibration control concerned in this research has been provided. The efficiency of MR dampers in seismic vibration suppression has been analysed. Further discussion in addition to two case studies has been provided in the following chapters.

CHAPTER 3

STRUCTURES WITH ACTIVE TUNED MASS DAMPERS

3.1. Introduction

Mitigation of external vibrations such as winds and earthquakes has been a critical aspect in designing buildings. Recent advances in technology allow engineers to design intelligent structures capable of counteracting undesirable vibrations by using active control devices in the design of a modern structure. Passive, semi-active and active control is becoming a specific part in the structural system. Active tuned mass dampers (ATMD) have been a popular area of research for some time and progress has been seen in this field (Nerves C, 1995), (Soong T, 1993). Fuzzy Logic controllers are one of the best active control algorithms since they are model free approaches to system identification and control which makes the system easier to design than developing an accurate mathematical model of the structural system needed for control system design (Samali B, 2003).

Tuned Mass Dampers dissipate vibratory energy through a set of damper and spring connecting a small mass to the main structure; they have a great effect in vibration suppression caused by low frequency loads and loads with frequencies near the fundamental frequency of the structure. Despite these advantages they have shown poor behaviour due to stochastic loads with high frequencies such as earthquakes. Therefore, Active Tuned Mass Dampers are the alternatives suggested. In this approach, two benchmark structures are being analysed; a five storey structure (Samali B, 2003) and a fifteen storey structure (Guclu R, 2008). The active vibration control is conducted by Fuzzy Logic controllers since they are one of the best active vibration control methods. Their behaviour in different mass ratios (mass of structure to mass of damper) and different locations in the structure is being investigated. Also the structure is imposed to El Centro earthquake. The main goal is comparing the displacement of the last storey and the inter-storey drifts due to the aforementioned changes for the two benchmarks.

3.2. Structural System

The building structure is considered to have n-degrees-of-freedom. The external excitations can be wind or earthquake. The equation of motion is presented below:

$$M\ddot{x} + C\dot{x} + Kx = \Gamma f + M\Lambda\ddot{x}_g; \tag{3.1}$$

where m is the mass of the structure, c is the damping of the structure, k is the stiffness of the structure, $x(t)$ is the displacement matrix, $\dot{x}(t)$ is the velocity matrix, $\ddot{x}(t)$ is the acceleration matrix of the building structure;

$x(t) = [x_1, x_2, \dots, x_n]^T$, $\dot{x}(t) = [\dot{x}_1, \dot{x}_2, \dots, \dot{x}_n]^T$, $\ddot{x}(t) = [\ddot{x}_1, \ddot{x}_2, \dots, \ddot{x}_n]^T$
$f = [f_1, f_2, \dots, f_n]^T$, $\Lambda = [1,1, \dots ,1]^T$.

Matrix Γ is the gain matrix determining the control effect on the building, Λ is a distribution matrix, f is the control force provided by the controller and $\ddot{x}_g(t)$ is the ground acceleration of the earthquake.

The mass matrix is considered as below:

$$M = diag([m_1, \dots, m_n]). \tag{3.2}$$

The stiffness matrix is as below:

$$K = \begin{bmatrix} k_1 + k_2 & -k_2 & 0 & 0 \\ -k_2 & \cdots & \cdots & 0 \\ 0 & \cdots & \cdots & -k_n \\ 0 & 0 & -k_n & k_n \end{bmatrix}. \tag{3.3}$$

The damping matrix is as below:

$$C = \begin{bmatrix} c_1 + c_2 & -c_2 & 0 & 0 \\ -c_2 & \cdots & \cdots & 0 \\ 0 & \cdots & \cdots & -c_n \\ 0 & 0 & -c_n & c_n \end{bmatrix}. \tag{3.4}$$

The equation of motion is transformed into state space equations in which a system state is defined $y = [x^T \quad \dot{x}^T]^T \in R^{2n}$ and has the below form:

$$\dot{y} = Ay + Bf + E; \tag{3.5}$$

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ M^{-1}\Gamma \end{bmatrix}, \qquad E = \begin{bmatrix} 0 \\ \Lambda \end{bmatrix} \ddot{x}_g \ ; \tag{3.6}$$

where A is the system matrix, B is the gain matrix and E is the external excitation matrix.

3.3. Building Structure equipped with Tuned Mass Dampers

The structural parameters (mass, stiffness and damping) as assumed (Samali B, 2003)(Guclu R, 2008) for the five and fifteen storey structures, are constant for every storey of the structure. The Tuned Mass Damper has a mass of 1, 2, 3 and 4 % of the total structural mass in different assumptions, and its frequency is tuned to the fundamental frequency of the structure and since it is located at the top of the structure, it is considered to be the sixteenth degree of freedom with its structural parameters (mass, stiffness and damping) being constant as if there were another storey on the last floor. The earthquake subjected to the structure is El Centro (M_w= 7.1), normalized to 2g as shown in figure 3.1. This quake is given by the strong motion database provided in Berkeley University (PEER berkeley Strong Motion Data base).

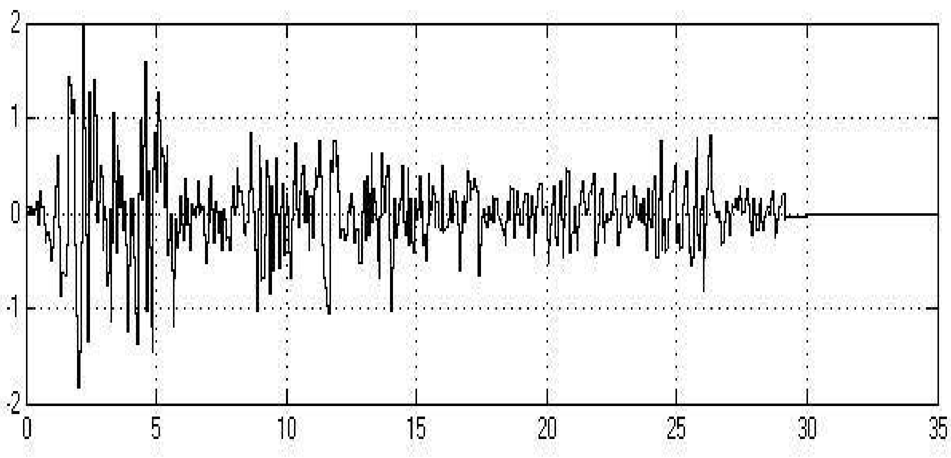


Figure 3.1. El Centro earthquake acceleration time history, normalised to 2g

As shown in equation 3.1, the earthquake is subjected to the structure. After the earthquake, the structure experiences a free vibration period in which there is no input exciting the structure. The force produced by the active control device throughout the earthquake excitation and the free vibration afterwards mitigates the energy of the external excitation.

3.4. Structural model of a five storey building structure

The five storey benchmark model, *3.6* m tall steel frame designed and manufactured at the University of Technology Sydney is used for this study as shown in figure 3.2. The model has a footprint of *1.5m* x *1.0m*. It consists of two bays in one direction and a single bay in the other. The beams making up the bulk of each floor are *75* x *75*x *4 mm* square hollow steel sections. The model lateral stiffness is provided by six high strength *24* x *24 mm* square steel sections. The model is designed to have the first floor heights of 0.7m. Taking advantage of the fact that masses are effectively lumped at the first floor levels, simplifies the analyses and hence the frame is represented by a five lumped mass dynamic system, yielding a *5* x *5* diagonal mass matrix for both orthogonal directions. The analysis, however, is a *2D* analysis focusing on the motion of the frame along its longer two bay directions. The total mass of the model is *1636.5 kg*. The five natural frequencies of the model are 2.95, 9.02, 15.68, 21.26 and 25.23 Hz, respectively, and the corresponding damping ratios are 0.4%, 0.69%, 0.63%, 0.2% and 0.14% of critical damping, respectively (Samali B, 2003).

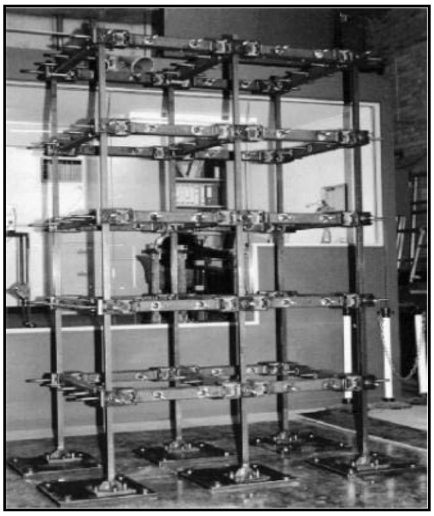


Figure 3.2. Five storey benchmark steel frame

3.4.1. Fuzzy Logic Controller design for the five storey structure

Fuzzy Logic control has been extensively introduced in Appendix D. The design of the Fuzzy controller uses crisp data directly from a number of sensors; these data are then converted into linguistic or Fuzzy membership functions through the fuzzification process. The number of sensors used in the system is dependent on the number of input variables used in the controller. The controller is designed using two input variables, each one having seven membership functions, and one output variable with eleven membership functions. The membership functions chosen for the input and output variables are triangular shaped as illustrated in figure 3.3. The Fuzzy variables used to define the Fuzzy space are described in table 3-1.The fuzzy associate memory (FAM) is shown in table 3-2. Two acceleration feedback sensors on floors 4 and 5 are used in the simulation of the system with Fuzzy controller because the response of the model is larger on the top floors compared to lower ones. Also, for this model, the higher modes are expected to have little contribution as their corresponding frequencies are away from dominant ground frequencies. The Fuzzy controller is implemented into SIMULINK program using an integration time step of 0.001 s and the control signal is computed every 0.001 s, accordingly, as shown in figure 3.4. In practice one runs the dynamic simulation, selects the state variable that seems to show the most severe response and then runs the controlled system using the extreme values of the selected state variables.

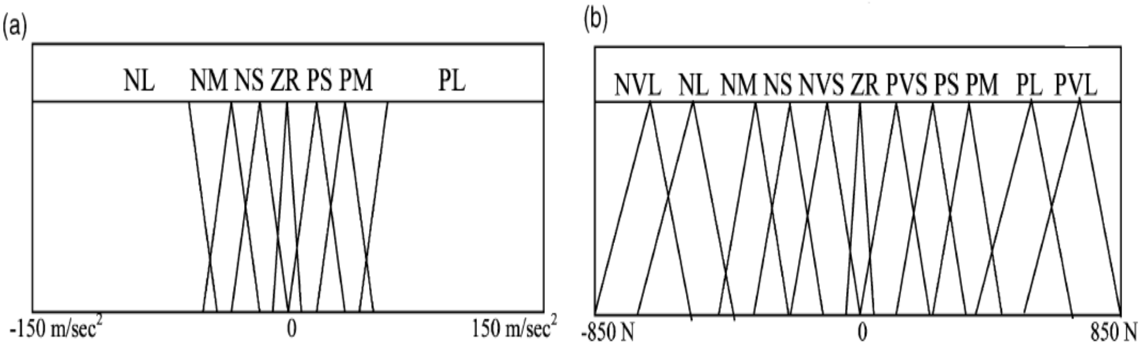


Figure 3.3. Membership function for; (a) the acceleration at levels 4 and 5; (b) control force

Table 3-1- Fuzzy Variables

PVL	Positive and very large
PL	Positive and large
PM	Positive and medium
PS	Positive and small
PVS	Positive and very small
ZR	Zero
NVS	Negative and very small
NS	Negative and small
NM	Negative and medium
NL	Negative and large
NVL	Negative and very large

Table 3-2- Fuzzy associative memory (FAM) of the Fuzzy Logic controller

	$\ddot{x}_4$							
$\ddot{x}_5$	U	NL	NM	NS	ZR	PS	PM	PL
	NL	NVL	NVL	NL	NM	PVS	PM	PL
	NM	NVL	NL	NL	NM	PVS	PM	PL
	NS	NL	NL	NM	NS	PVS	PM	PL
	ZR	NL	NM	NS	ZR	PS	PM	PL
	PS	NL	NM	NVS	PS	PM	PL	PL
	PM	NL	NM	NVS	PM	PL	PL	PVL
	PL	NL	NM	NVS	PM	PL	PVL	PVL

The simulation analysis of the five storey benchmark model without control, with ATMD system using Fuzzy Logic controllers are implemented into the SIMULINK program.

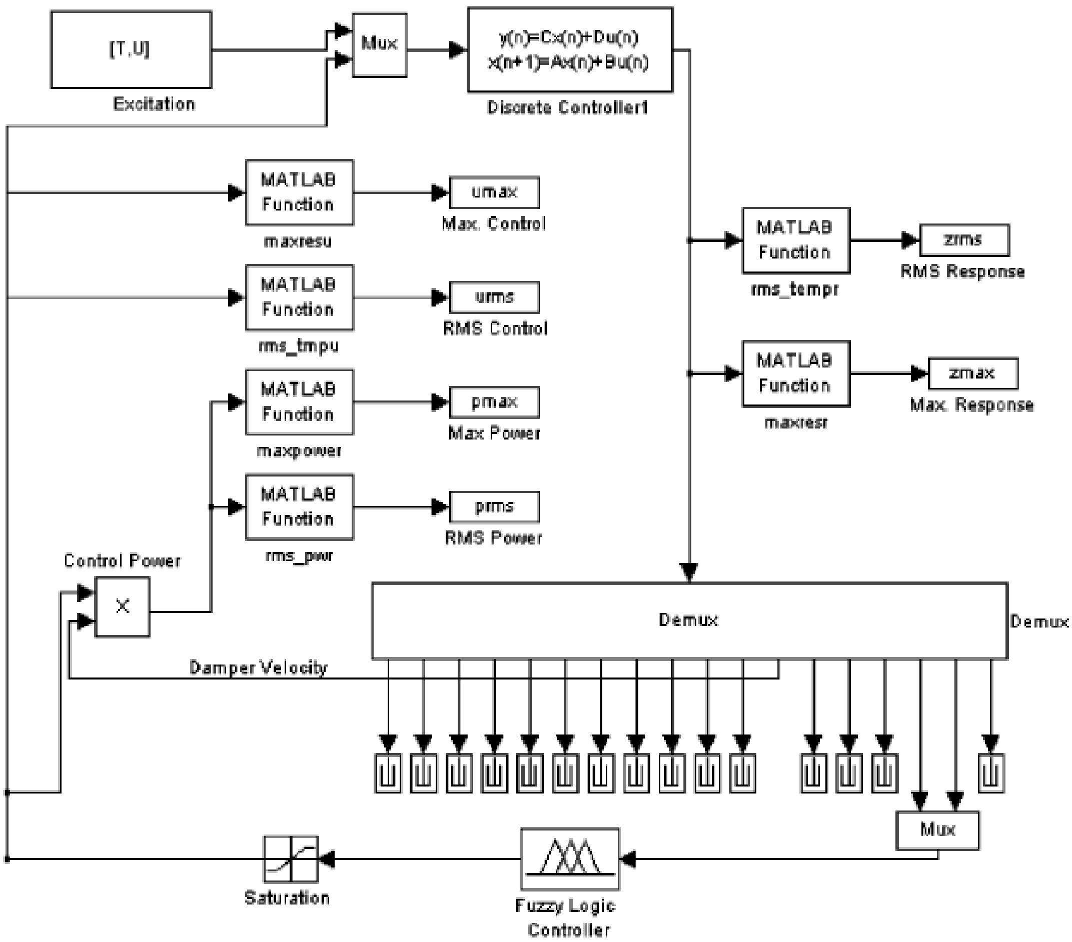


Figure 3.4. Simulink model of the five storey building with Fuzzy Logic controllers

3.5. Structural model of a fifteen storey building structure

The structure has fifteen degrees of freedom all in horizontal direction. Since the destructive effect of earthquakes is the result of horizontal vibrations, in this study the degrees of freedom have been assumed only in this direction. The system is modelled including the dynamics of a linear motor which is used as the active isolator. An important element of an active control strategy is the actuators (R. Agarwala, 2000).These are active control devices that expend energy to attenuate disturbances at the corresponding subsystems or reduce the storey vibration on which they are installed.

During an earthquake, the maximum inter-storey shear force occurs on the first storey. Assuming equivalent storey stiffness and ultimate capacities, the destructive effect of an earthquake is expected to be the largest on the first storey. Therefore, the active control was applied on the first storey using a linear motor. It supplies control voltage directly to suppress the magnitude of undesirable earthquake vibrations.

It is well known that the maximum displacements and accelerations are expected from the top storey of structures during an earthquake. Because of that an ATMD with active and passive elements, which are optimally tuned for the first mode of the structural system, is placed over the top storey and a linear motor is used as the active isolator.

The system parameters of the real structure (Gozukizil, 2000) are presented in table 3-3.

Table 3-3- Parameters of the fifteen storey structural system

Mass parameters (kg)	**Stiffness parameters (N/m)**	**Damping parameters (N s/m)**
m_1 = 450,000	k_1 = 18,050,000	c_1 =26,170
m_2 = 345,600	k_2 = 340,400,000	c_2 = 293,700
m_3 = 345,600	k_3 = 340,400,000	c_3 = 293,700
m_4= 345,600	k_4 = 340,400,000	c_4 = 293,700
m_5= 345,600	k_5 = 340,400,000	c_5 = 293,700
m_6 = 345,600	k_6 = 340,400,000	c_6 = 293,700
m_7= 345,600	k_7 = 340,400,000	c_7 = 293,700
m_8 = 345,600	k_8 = 340,400,000	c_8 = 293,700
m_9= 345,600	k_9 = 340,400,000	c_9 = 293,700
m_{10} = 345,600	k_{10} = 340,400,000	c_{10} = 293,700
m_{11} = 345,600	k_{11} = 340,400,000	c_{11} = 293,700
m_{12} = 345,600	k_{12} = 340,400,000	c_{12} = 293,700
m_{13} = 345,600	k_{13} = 340,400,000	c_{13} = 293,700
m_{14} = 345,600	k_{14} = 340,400,000	c_{14} = 293,700
m_{15} = 345,600	k_{15} = 340,400,000	c_{15} = 293,700

3.5.1. Fuzzy Logic Controller design for the fifteen storey structure

The Fuzzy Toolbox in MATLAB in SIMULINK is used. In the fuzzy logic control for the structural system, the errors (e $=x_{r2}$-x_2; e_1 $=x_{r15}$-x_{15}) in the second storey and fifteenth storey motion and their derivatives (de/dt $=\dot{x}_{r2}$-$\dot{x}_2$), (de$_1$/dt = $\dot{x}_{r15}$-$\dot{x}_{15}$) are used as the input variable while the control voltages (u) and (u_{ATMD}) are the outputs. Reference values (x_{r2};$\dot{x}_{r2}$) and (x_{r15};$\dot{x}_{r15}$) are considered to be zero in the closed-loop model of the system (figure 3.5).

A model of the two similar rule bases developed by heuristics with error in body bounce motion, pitch motion and velocity as input variables are given in table3-4, where P, N, Z, B, M, S represent positive, negative, zero, big, medium and small, respectively. Trial and error approach with triangular membership functions has been used to achieve a good controller performance. The membership functions for both scaled inputs *(e,de)* and output *(u)* of the controller have been defined on the common interval [-1, 1] (Figure 3.5). Scaling factors (Se, Sde, *Su* and *Se1, Sde1, Su1*) are used to set *e, de* and *u* in figure 3.5 (R.K. Mudi, 1999) and introduced in table 3-6.

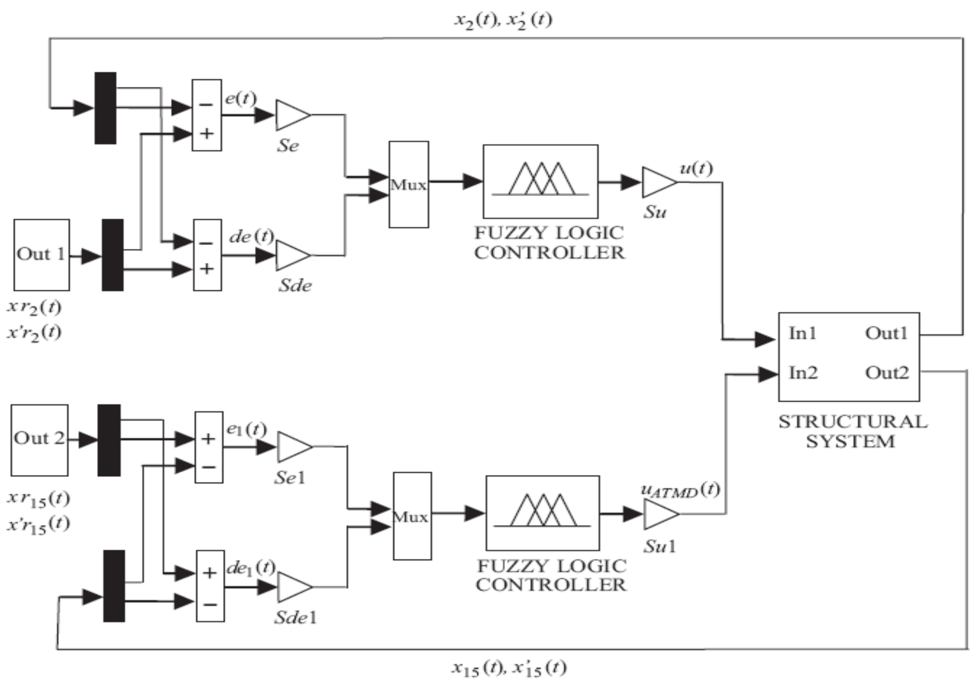


Figure 3.5. Closed-loop model of the fifteen storey structure with fuzzy logic controllers

The first rule in table 3-4is given as IF e is XNB and de/dt is VN, THEN u is UNB.

All the rules are written using Mamdani method to apply to fuzzification presented below. In this study, the centroid method is used in defuzzification.

Table 3-4- Rule base definition for the fuzzy logic controllers in the fifteen storey structure

Error (e)	**Velocity of the error (de/dt)**		
	VN	VZ	VP
XNB	UNB	UNM	UNS
XNS	UNM	UNS	UZ
XZ	UNS	UZ	UPS
XPS	UZ	UPS	UPM
XPB	UPS	UPM	UPB

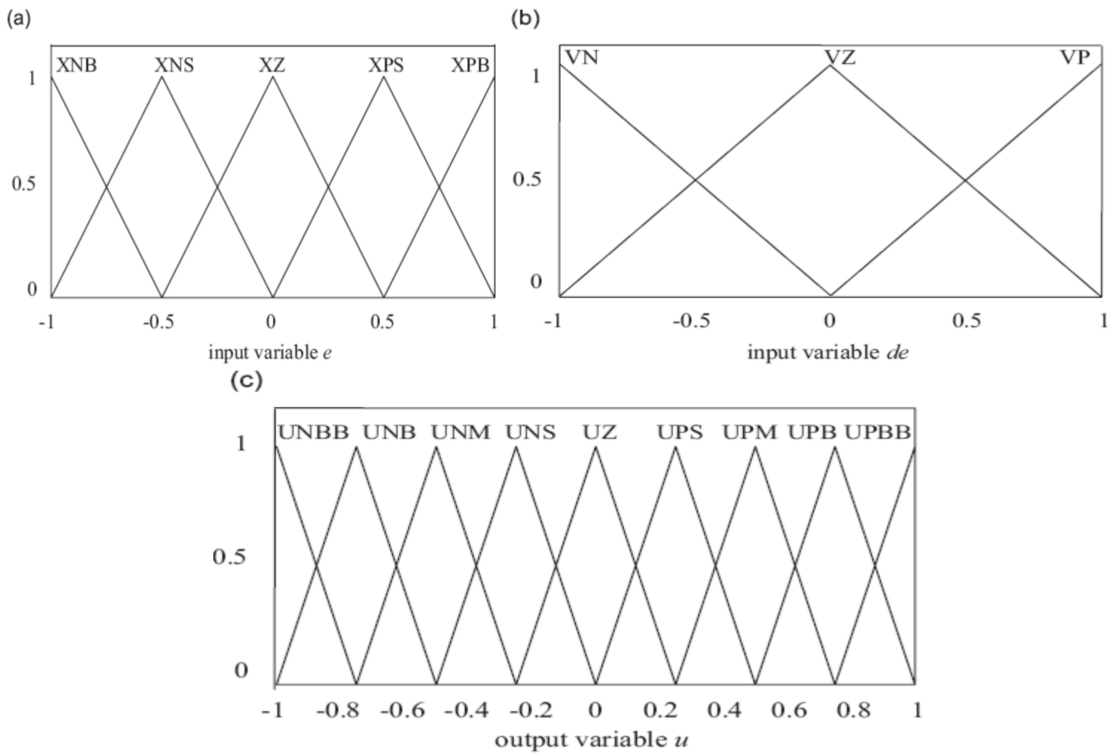


Figure 3.6. Membership functions of (a) error (e), (b) derivative of error (de/dt), (c) control signal (u)

Table 3-5- Rules for the fuzzy logic controller in the fifteen storey structure

If (e is XNB) and (de is VN) then (u is UNB)
If (e is XNB) and (de is VZ) then (u is UNM)
If (e is XNB) and (de is VP) then (u is UNS)
If (e is XNS) and (de is VN) then (u is UNM)
If (e is XNS) and (de is VZ) then (u is UNM)
If (e is XNS) and (de is VP) then (u is UNM)
If (e is XZ) and (de is VN) then (u is UNS)
If (e is XZ) and (de is VZ) then (u is UZ)
If (e is XZ) and (de is VP) then (u is UNS)
If (e is XPS) and (de is VN) then (u is UZ)
If (e is XPS) and (de is VZ) then (u is UPS)
If (e is XPS) and (de is VP) then (u is UPM)
If (e is XPB) and (de is VN) then (u is UPS)
If (e is XPB) and (de is VZ) then (u is UPM)
If (e is XPB) and (de is VP) then (u is UPS)

Table 3-6- Scaling factors for the actuators installed in the fifteen storey building

FLC input–output scaling factors for actuator which is installed first storey	FLC input–output scaling factors for ATMD
Se = 40	Se1 = 5
Sde = 0.9	Sde1 = 0.9
Su = 5,800,000	Su1 = 24,700,000

In all the above cases, the Fuzzy Logic controller for the five storey structure is defined in Samali (Samali B, 2003) and for the fifteen storey structure is defined in Guclu (Guclu R, 2008).

3.6. Structural Response considering different changes in Active Tuned Mass Dampers for the five and fifteen storey structures

Different cases are being considered in which the active tuned mass damper has different mass ratios for the five and fifteen storey structure. In all the below cases, the active control device is at the top floor and the controller is a Fuzzy Logic controller. This controller has a tool box in MATLAB.

The first case considered here is:

- For the five storey structure, the Active Tuned Mass Damper has different mass ratios, 1 to 4% of the mass of the total structure mass and is tuned in all cases to the fundamental frequency of the main structure. For the five storey structure, the displacement of the last storey is shown in figures 3.7 to 3.10 and for the fifteen storey structure; it is shown in figures 3.12 to 3.15. Figures 3.11 and 3.16 are the displacements of the sole ATMD at the top floor for the five and fifteen storey structure.

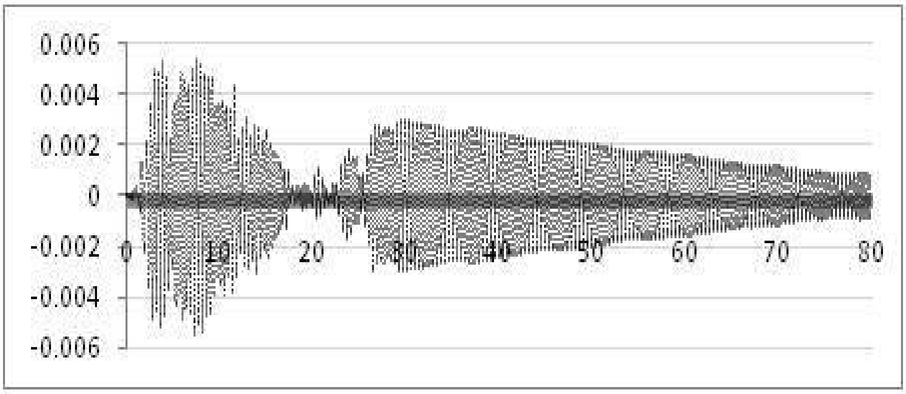


Figure 3.7. Displacement of the last storey (m) versus time, ATMD mass ratio of 1%, under El Centro quake, five storey structure

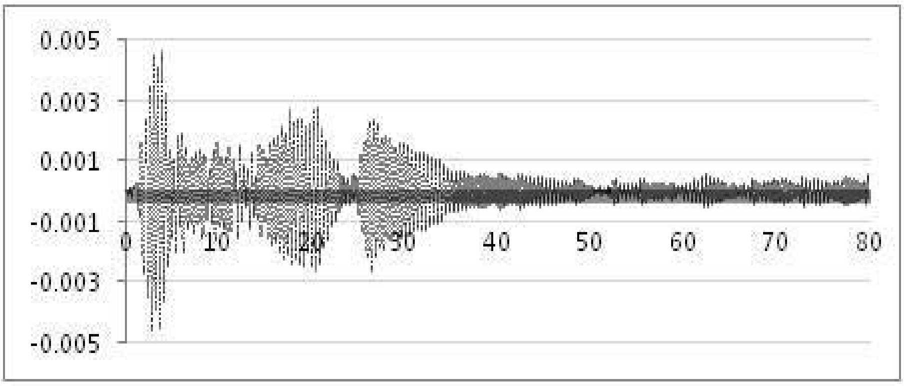


Figure 3.8. Displacement of the last storey (m) versus time, ATMD mass ratio of 2%, under El Centro quake, five storey structure

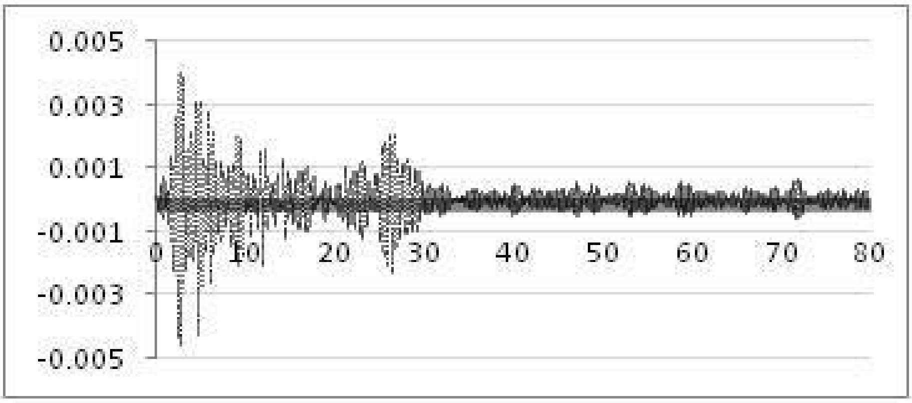


Figure 3.9. Displacement of the last storey (m) versus time, ATMD mass ratio of 3%, under El Centro quake, five storey structure

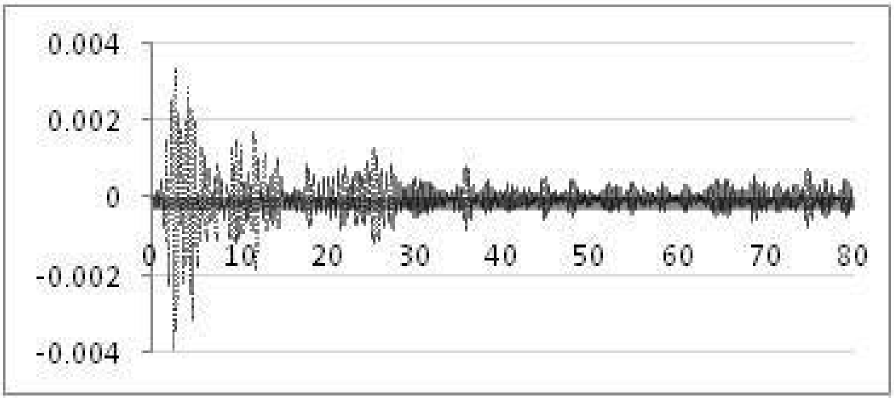


Figure 3.10. Displacement of the last storey (m) versus time, ATMD mass ratio of 4%, under El Centro quake, five storey structure

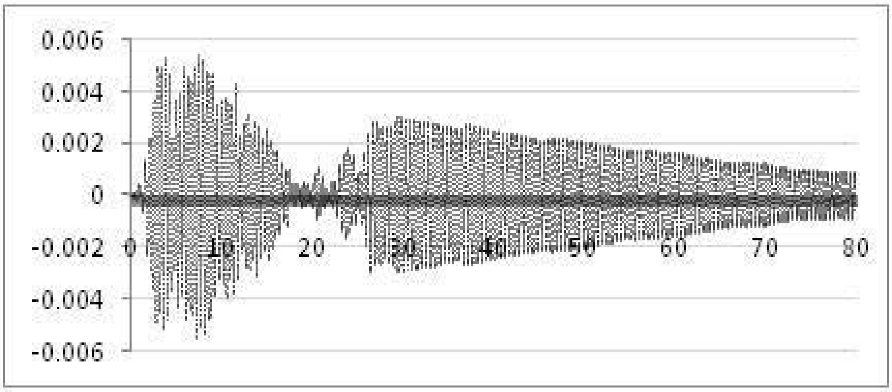


Figure 3.11. Displacement of sole ATMD at the top floor (m) versus time, under El Centro, five storey structure

The second case considered here is:

- For the fifteen storey structure, the Active Tuned Mass Damper has different mass ratios, 1 to 4% of the mass of the total structure mass and is tuned in all cases to the fundamental frequency of the main structure.

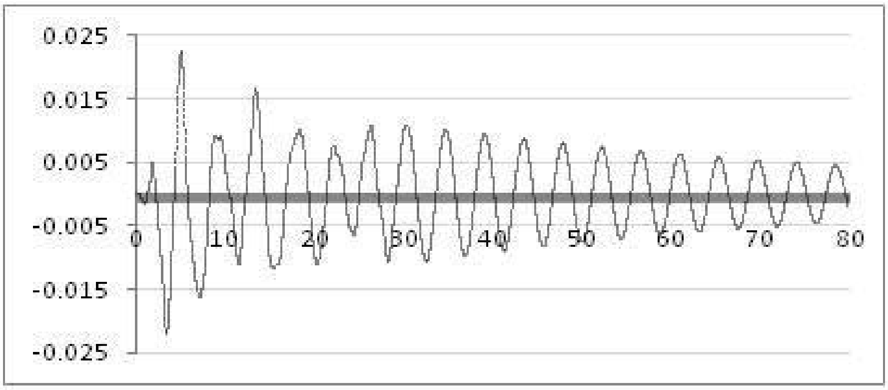


Figure 3.12. Displacement of the last storey (m) versus time, ATMD mass ratio of 1%, under El Centro quake, fifteen storey structure

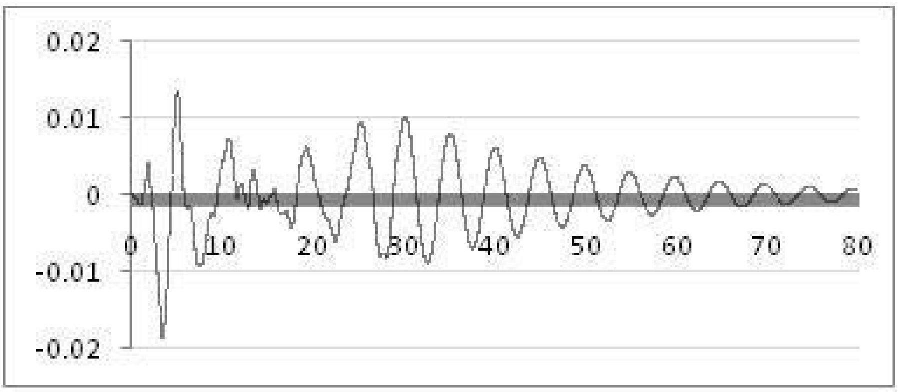


Figure 3.13. Displacement of the last storey (m) versus time, ATMD mass ratio of 2%, under El Centro quake, fifteen storey structure

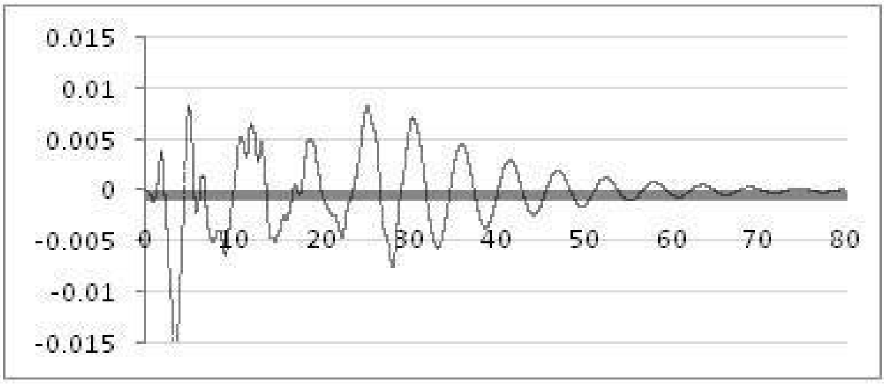


Figure 3.14. Displacement of the last storey (m) versus time, ATMD mass ratio of 3%, under El Centro quake, fifteen storey structure

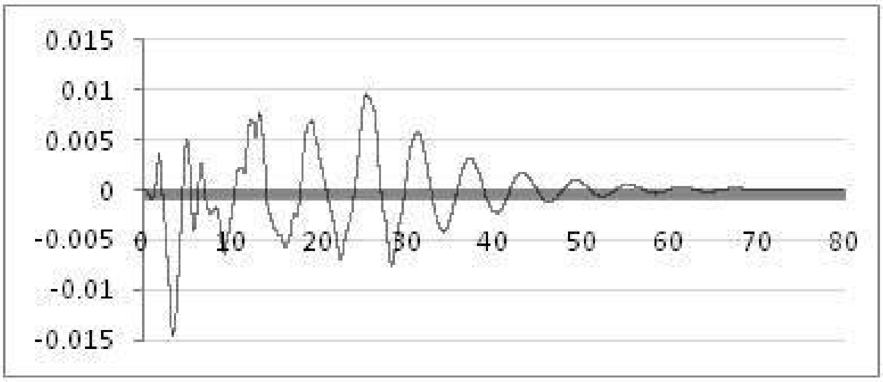


Figure 3.15. Displacement of the last storey (m) versus time, ATMD mass ratio of 4%, under El Centro quake, fifteen storey structure

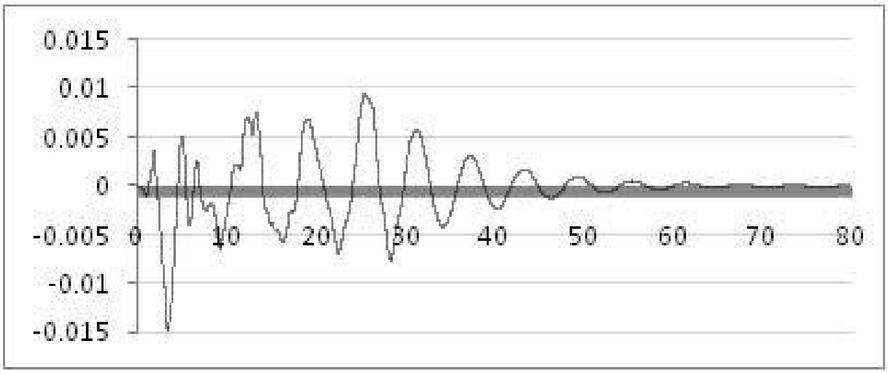


Figure 3.16. Displacement of sole ATMD at the top floor (m) versus time, under El Centro quake, fifteen storey structure

3.7. Structural Response considering Tuned Mass Dampers in different locations for the five and fifteen storey structure

The third case considered here is:

- For the five storey structure, the ATMD is in one case, on top of the structure and in another case there are two ATMDs one at the top, the second one at the third floor or at the first floor being compared.

The fourth case considered here is:

- For the fifteen storey structure, the ATMD is in one case, on top of the structure and in another case there are two ATMDs one at the top, the second one at the eleventh floor or at the seventh floor or at the third floor being compared.

The displacements of some storeys are shown when the ATMDs are in different locations for the five and fifteen storey structures.

- For the five storey structure, figure 3.17 shows the displacement of the last storey when one ATMD is installed on the first and one on the fifth storey. Figure 3.18 shows the displacement of the ATMDs when one is on the third floor and one on the fifth floor.

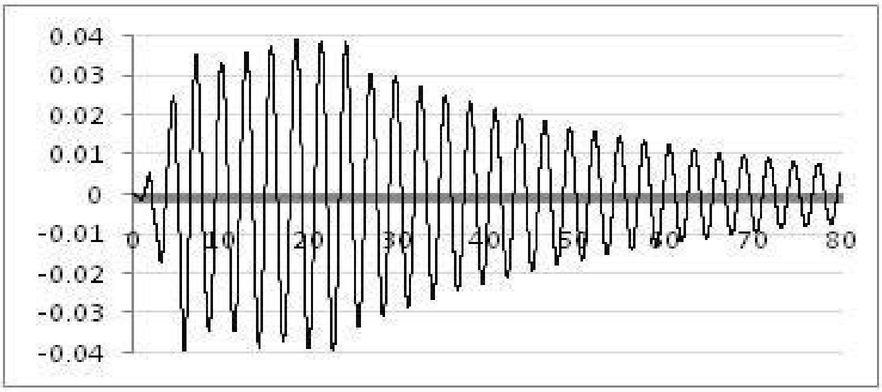


Figure 3.17. Displacement of the fifth floor (m) versus time, 1st floor ATMD + 5th floor ATMD, under El Centro quake, five storey structure

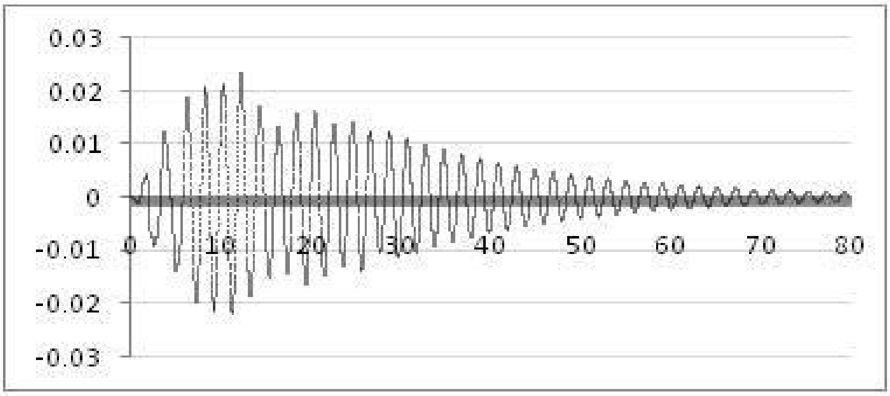


Figure 3.18. Displacement of the fifth floor (m) versus time, 3rd floor ATMD + 5th floor ATMD, under El Centro quake, five storey structure

- For the fifteen storey structure, figures 3.19 and 3.20 shows the displacement of the third and the last storey when the ATMDs are installed on the third and fifteenth floor.

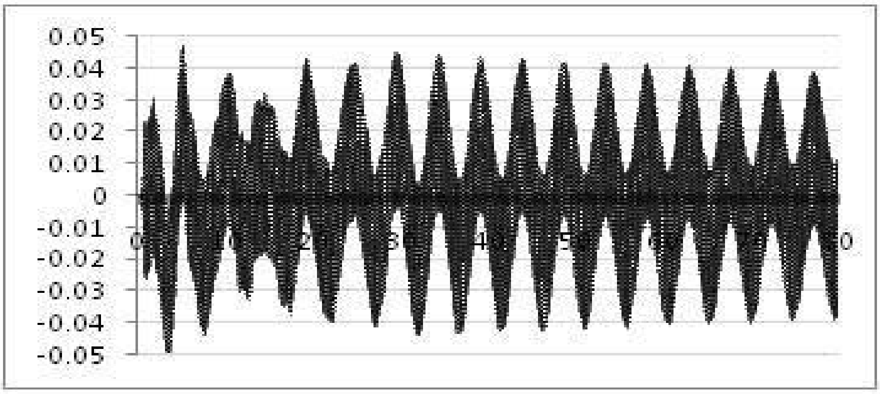


Figure 3.19. Displacement of the third floor (m) versus time, 3rd floor ATMD + 15th floor ATMD, under El Centro quake, fifteen storey structure

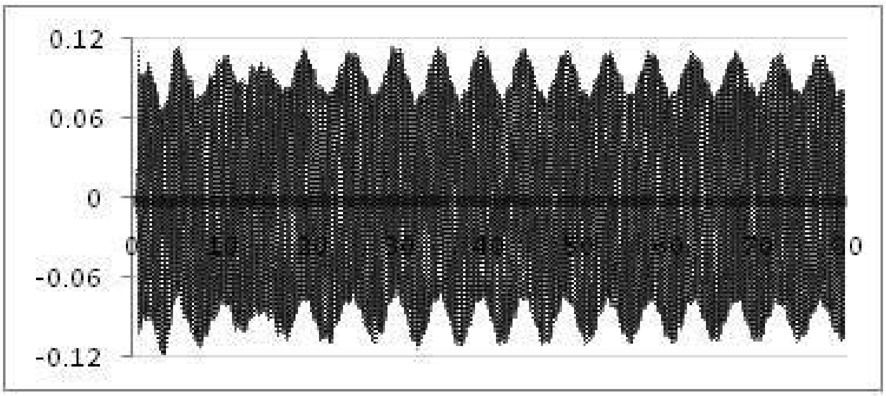


Figure 3.20. Displacement of the fifteenth floor (m) versus time, 3rd floor ATMD + 15th floor ATMD, under El Centro quake, fifteen storey structure

• For the fifteen storey structure, figures 3.21 and 3.22 shows the displacement of the seventh and last storey when the ATMDs are installed on the seventh and fifteenth floor.

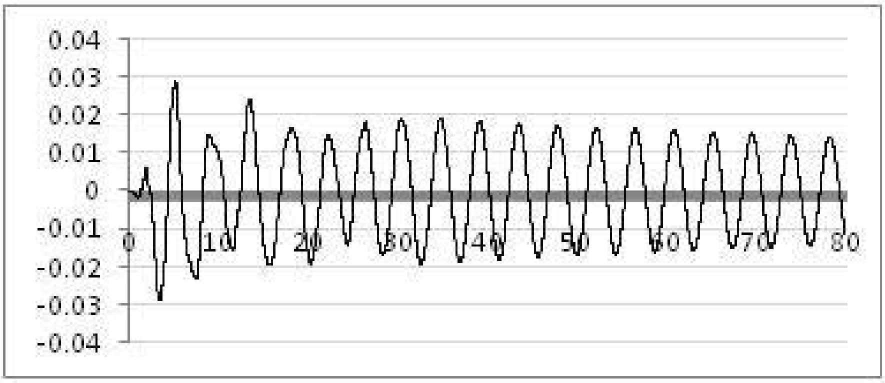


Figure 3.21. Displacement of the seventh floor (m) versus time, 7th floor ATMD + 15th floor ATMD, under El Centro quake, fifteen storey structure

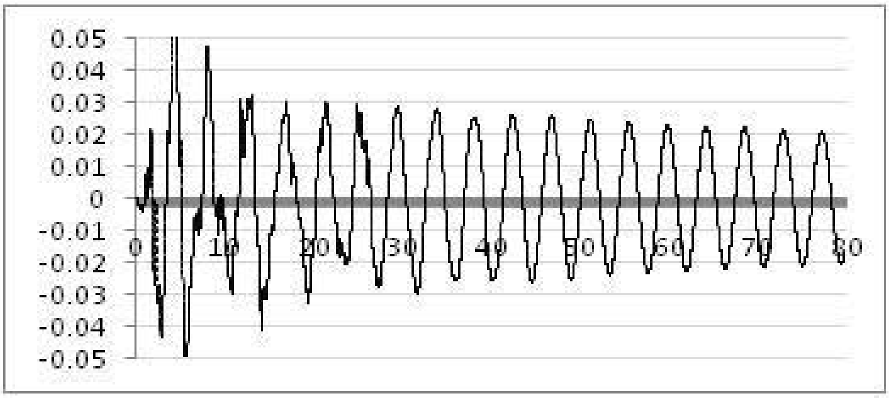


Figure 3.22. Displacement of the fifteenth floor (m) versus time, 7th floor ATMD + 15th floor ATMD, under El Centro quake, fifteen storey structure

• For the fifteen storey structure, figures 3.23 to 3.24 shows the displacement of the thirteenth and last storey when the ATMDs are installed on the thirteenth and fifteenth floor.

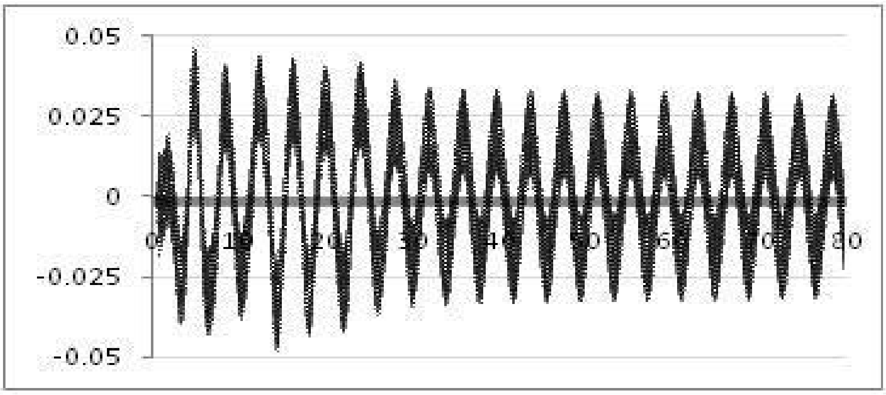


Figure 3.23. Displacement of the thirteenth floor (m) versus time, 13th floor ATMD + 15th floor ATMD, under El Centro quake, fifteen storey structure

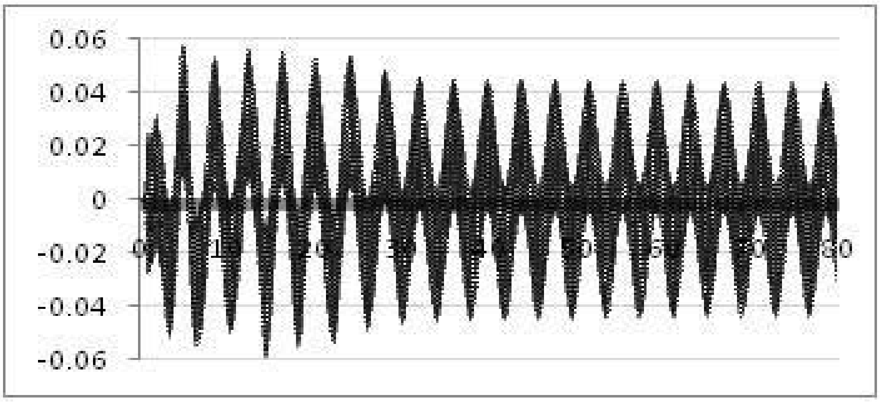


Figure 3.24. Displacement of the fifteenth floor (m) versus time, 13th floor ATMD + 15th floor ATMD, under El Centro quake, fifteen storey structure

3.8. Conclusion

When ATMD (active tuned mass damper) is installed in the five and fifteen storey structure, the displacement of the last storey is estimated considering different mass ratios (= mass of ATMD / mass of structure) ranging from 1 to 4%. Both for the five and fifteen storey structure, it is observed that as the mass ratio approaches 4%, the displacement of the last storey reduces to nearly zero. Therefore, the mass of the ATMD has considerable effect on the seismic reduction of displacement due to El Centro earthquake.

The ATMD is located in different floors. In some cases there is more than one ATMD, each located in different floors. For the five storey structure, in one case, there are two ATMDs one located on the first and one on the fifth floor. In another case, there are two ATMDs one located on the third and one on the fifth floor. The displacement of the last storey is reduced considerably in the case when there is one ATMD at the top and one in mid-height of the structure in contrast to one ATMD at the top storey and one at the first storey. For the fifteen storey structure, in one case, there are two ATMDs one located on the third floor and one at the last floor. In the second case, there are two ATMDs one located on the seventh floor and one at the last floor. In the third case, there are two ATMDs one located on the thirteenth floor and one at the last floor. The simulation results show one ATMD being located on the mid-height of the structure and one at the top has the highest effect on the seismic vibration reduction due to El Centro earthquake.

CHAPTER 4

ACTIVE VIBRATION CONTROL OF TWO BENCHMARK STRUCTURES EQUIPPED WITH MULTIPLE TUNED MASS DAMPERS

4.1. Introduction

The tuned mass damper (TMD) is an energy dissipation device, which suppresses structural vibration by transferring some of the structural vibration energy to the TMD and dissipates the energy through the damping of the TMD (Hong-Nan Li, 2007). However, single tuned mass damper (STMD) is sensitive to the frequency ratio between the TMD and the structure and the damping ratio of the TMD. The effectiveness of STMD is reduced significantly due to the mistuning or off optimum damping. As a result, the use of more than one TMD with different dynamic characteristics has been proposed by Xu and Igusa (K. Xu, 1992) in order to improve the effectiveness and robustness.

The multiple tuned mass dampers (MTMDs) for controlling the structural vibration consist of a large number of small TMDs whose natural frequencies are distributed around the natural frequency of a controlled mode of the structure (Hong-Nan Li, 2007).

Xu and Igusa (K. Xu, 1992) studied the case of multiple substructures with light damping and equal spacing over a frequency range can be more effective and more robust than a single TMD with equal total mass when the system is excited by a wide band random excitation.

In this chapter, the two benchmark structures from the previous chapter are being analysed; a five storey structure (Samali B, 2003) and a fifteen storey structure (Guclu R, 2008) this time equipped with Multiple Active Tuned Mass Dampers. Multiple mass dampers are used with the intention of covering a higher frequency range compared to sole tuned mass dampers. The active control is carried out by Fuzzy Logic controllers for each of the dampers on the top floor. These controllers all have the same membership functions and same rules in which during the earthquake subjected to the structure and the free vibration afterwards, the actuators are producing control forces in each time step to mitigate the external vibration damaging the structure.

The tuned mass dampers are considered in two cases. In the first case, they have equivalent mass; considering different frequency parameters. In the second case, they have equivalent stiffness and damping parameters; considering different mass.

The aforementioned structures are exposed to El Centro earthquake (M_w = 7.1), normalized to 0.5g as the Peak Ground Acceleration (PGA). The considerably reduced structural response (displacements of the last storey) is compared with Active Multiple Tuned Mass Dampers (AMTMDs) and Active Tuned Mass Dampers (ATMDs). By exposing the structure to this earthquake, the vibration suppression of AMTMDs is shown to be highly superior to ATMD. It is also shown that increasing the height of the structure helps maintain higher energy dissipation.

4.2. Structural Model of bench mark structures

The bench mark structures analysed here are the five storey structure (Samali B, 2003) and the fifteen storey structure (Guclu R, 2008) mentioned in the previous chapter.

As discussed in earlier chapters, the equation of motion of the two aforementioned structures is:

$$[M]\ddot{x}+[C]\dot{x}+[K]x=F_{quake}+F_u \tag{4.1}$$

In the equation above:

F_{quake} is the earthquake subjected to the structure. After the quake, the structure experiences a free vibration period in which there is no input exciting the structure. F_u is the force produced by the active control device throughout the earthquake vibration and the free vibration afterwards.

The active control is performed using Fuzzy Logic controllers exactly as assumed in the five storey structure by Samali (Samali B, 2003) and the fifteen storey structure by Guclu (Guclu R, 2008).

The two structures are subjected to El Centro earthquake (M_w = 7.1), normalized to 0.5g as the Peak Ground Acceleration (PGA). This earthquake is provided by the strong motion data base in University of Berkeley at California (PEER berkeley Strong Motion Data base).

In order to solve the coupled equations above, a state space model is presented:

$$\begin{aligned}\dot{x} &= Ax + Bu + Ew\\ y &= Cx + Du + Fw\end{aligned} \tag{4.2}$$

where x is the state vector, y is the output vector, u is the control force, w is the earthquake excitation. A is the system matrix, B is the control location vector, E is the excitation location vector. C, D and F are matrices of appropriate dimensions. Equation (4.1) is solved by turning it into the form of equation (4.2), so it can be solved numerically in MATLAB. The structural responses are provided by SIMULINK in MATLAB.

In the Multiple Tuned Mass Damper case for equation (4.1), the mass, stiffness and damping matrices are different to the sole Tuned Mass Damper case. In the sole Tuned Mass Damper case, the structure is modelled with a mass on top which has constant values for mass and stiffness and damping throughout the earthquake and the free vibration afterwards and so an additional degree of freedom is added to the structure which is modelled as another storey on top. For the Multiple Tuned Mass Damper case, there are multiple additional degrees of freedom added to the structure. The configuration of these dampers is shown in figure 4.1.

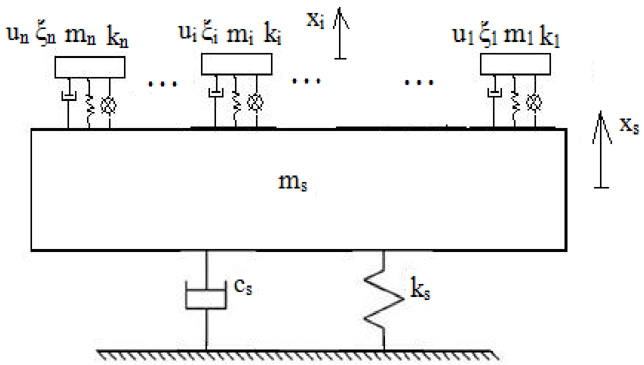


Figure 4.1. Active Multiple Tuned Mass Dampers (AMTMDs)

As mentioned above, in the case of Multiple Tuned Mass Dampers, the mass and stiffness and damping matrices differ compared to Tuned Mass Dampers. These matrices are shown below (Hong-Nan Li, 2007):

$$x = [x_s \quad x_{t1} \quad x_{t2} \quad \cdots \quad x_n]^T \qquad \text{, n = No. of TMDs} \tag{4.3}$$

$$M = diag[m_s \quad m_{t1} \quad m_{t2} \quad \ldots \quad m_{tn}] \qquad \text{, } m_{tj} = \text{mass of the } j^{th} \text{ damper} \tag{4.4}$$

$$K = \begin{bmatrix} k_s + \sum_{k=1}^{n} k_k & -k_1 & -k_2 & \cdots & -k_n \\ -k_1 & k_1 & 0 & \cdots & 0 \\ -k_2 & 0 & k_2 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -k_n & 0 & 0 & \cdots & k_n \end{bmatrix} \tag{4.5}$$

$$C = \begin{bmatrix} c_s + \sum_{k=1}^{n} c_k & -c_1 & -c_2 & \cdots & -c_n \\ -c_1 & c_1 & 0 & \cdots & 0 \\ -c_2 & 0 & c_2 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -c_n & 0 & 0 & \cdots & c_n \end{bmatrix} \tag{4.6}$$

4.3. Multiple tuned mass damper configuration

The structural modelling of the five and fifteen storey structures equipped with multiple tuned mass dampers is presented here. Two cases are being considered, but first some terms need to be explained (Siyassi, 2003):

Average frequency of MTMDs:

$$\omega_T = \sum_{k=1}^{n} \frac{\omega_k}{n} \quad , \text{ n = No. of MTMDs} \tag{4.7}$$

Frequency space for the MTMDs:

$$\beta = \frac{\omega_n - \omega_1}{\omega_T} \tag{4.8}$$

Frequency of the j^{th} MTMD:

$$\omega_j = \omega_T + \Delta\omega_j \quad , \ j = 1, 2, \ldots, n \tag{4.9}$$

$$\Delta\omega_j = \omega_T \left(j - \frac{n+1}{2}\right) \frac{\beta}{n-1}$$

Mass ratio:

$$\mu = \frac{\sum_{j=1}^{n} m_j}{m_s} \quad , \ m_s = \text{mass of the total structure} \tag{4.10}$$

Average stiffness of the MTMDs:

$$K_T = \frac{\mu . m_s}{\sum_{j=1}^{n} \frac{1}{\omega_j^2}} \tag{4.11}$$

Mass of the j^{th} MTMD:

$$m_j = \frac{K_T}{\omega_j^2} \tag{4.12}$$

4.4. Active Vibration Control of the two benchmark structures

The active vibration control is performed by Fuzzy Logic Controllers. There are five membership functions for each input and nine for the output. All of these are triangular. The inputs are the displacement (XNB, XNS, XZ, XPS, XPB) and velocity (VNB, VNS, VZ, VPS, VPB) of the particular storey and the output is the control force (UNBB, UNB, UNM, UNS, UZ, UPS, UPM, UPB, UPBB) produced by the controller. The fuzzy logic procedure is performed by the fuzzy logic toolbox provided in MATLAB.

Table 4-1- Rule base definition for the fuzzy logic controller

Error (e)	Velocity of the error (de/dt)				
	VNB	VNS	VZ	VPS	VPB
XNB	UNBB	UNB	UNM	UNS	UZ
XNS	UNB	UNM	UNS	UZ	UPS
XZ	UNM	UNS	UZ	UPS	UPM
XPS	UNS	UZ	UPS	UPM	UPB
XPB	UZ	UPS	UPM	UPB	UPBB

The fuzzy rules are as follows:

1. If (x_2 is XNB) and (v_2 is VNB) then (u_2 is UNBB)
2. If (x_2 is XNB) and (v_2 is VNS) then (u_2 is UNB)
3. If (x_2 is XNB) and (v_2 is VZ) then (u_2 is UNM)
4. If (x_2 is XNB) and (v_2 is VPS) then (u_2 is UNS)
5. If (x_2 is XNB) and (v_2 is VPB) then (u_2 is UZ)
6. If (x_2 is XNS) and (v_2 is VNB) then (u_2 is UNB)
7. If (x_2 is XNS) and (v_2 is VNS) then (u_2 is UNM)
8. If (x_2 is XNS) and (v_2 is VZ) then (u_2 is UNS)
9. If (x_2 is XNS) and (v_2 is VPS) then (u_2 is UZ)
10. If (x_2 is XNS) and (v_2 is VPB) then (u_2 is UPS)
11. If (x_2 is XZ) and (v_2 is VNB) then (u_2 is UNM)
12. If (x_2 is XZ) and (v_2 is VNS) then (u_2 is UNS)
13. If (x_2 is XZ) and (v_2 is VZ) then (u_2 is UZ)
14. If (x_2 is XZ) and (v_2 is VPS) then (u_2 is UPS)
15. If (x_2 is XZ) and (v_2 is VPB) then (u_2 is UPM)
16. If (x_2 is XPS) and (v_2 is VNB) then (u_2 is UNS)
17. If (x_2 is XPS) and (v_2 is VNS) then (u_2 is UZ)
18. If (x_2 is XPS) and (v_2 is VZ) then (u_2 is UPS)
19. If (x_2 is XPS) and (v_2 is VPS) then (u_2 is UPM)
20. If (x_2 is XPS) and (v_2 is VPB) then (u_2 is UPB)
21. If (x_2 is XPB) and (v_2 is VNB) then (u_2 is UZ)
22. If (x_2 is XPB) and (v_2 is VNS) then (u_2 is UPS)
23. If (x_2 is XPB) and (v_2 is VZ) then (u_2 is UPM)
24. If (x_2 is XPB) and (v_2 is VPS) then (u_2 is UPB)
25. If (x_2 is XPB) and (v_2 is VPB) then (u_2 is UPBB)

where P, N, Z, B, M and S stand for positive, negative, zero, big, medium and small and X, V and U represent displacement, velocity and voltage.

4.5. Structural Modelling of the five storey structure

In the first case, there is only one ATMD at the top of the structure and the mass of this damper is 1% of the sum of the total mass of the structure. The critical damping is 0.02 of the critical damping of the structure. The active vibration control procedure is performed by only one Fuzzy Logic controller and the active control device is on the last floor. The fuzzy membership functions and rules are discussed above. The structure is exposed to El Centro earthquake, normalized to 0.5g. The response of the structure due to these external vibrations and the vibration suppression due to the active control device is shown in the figures below.

Table 4-2- Structural characteristics of the sole ATMD, five storey structure

m_{t1}(kgr)	17
K_{t1}(N/m)	2500
C_{t1}(Ns/m)	8

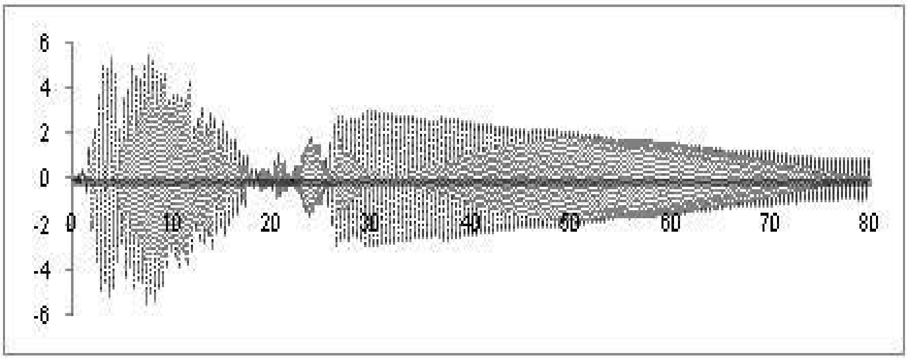


Figure 4.2. Last storey displacement (mm) versus time with a sole ATMD on top, the five storey structure

In the second case, there are three ATMDs at the top of the structure and the sum of the mass of these dampers is 1% of the sum of the total structures mass, the critical damping is 0.02 of the critical damping of the structure. The active vibration control procedure is performed by three Fuzzy Logic controllers for each of the tuned mass dampers and the active control devices are at the last floor. The fuzzy membership functions and rules are discussed above. The frequency space *(β)* is 0.3. This case is divided into two sub cases. In the first sub case, the mass of the AMTMDs is equal and in the second sub case, the damping and stiffness of the AMTMDs are equal. The structural characteristics of the AMTMDs for the two cases and the two sub cases are mentioned in the table below. Note that in all the fuzzy controllers the type and number of the membership functions and the rules are the same.

Table 4-3- Structural characteristics of the 3ATMDs, five storey structure, equal mass

m_{t1}(kgr)	6
m_{t2}(kgr)	6
m_{t3}(kgr)	6
K_{t1}(N/m)	600
K_{t2}(N/m)	900
K_{t3}(N/m)	1200
C_{t1}(Ns/m)	2
C_{t2}(Ns/m)	3
C_{t3}(Ns/m)	4

Table 4-4- Structural characteristics of the 3ATMDs, five storey structure, non-equal mass

m_{t1}(kgr)	7
m_{t2}(kgr)	5
m_{t3}(kgr)	4
K_{t1}(N/m)	840
K_{t2}(N/m)	840
K_{t3}(N/m)	840
C_{t1}(Ns/m)	3
C_{t2}(Ns/m)	3
C_{t3}(Ns/m)	3

The last storey displacement for the five storey structure with AMTMDs on top, with equal mass is shown in figure 4.3. The last storey displacement for the five storey structure with AMTMDs on top, with non-equal mass is shown in figure 4.4.

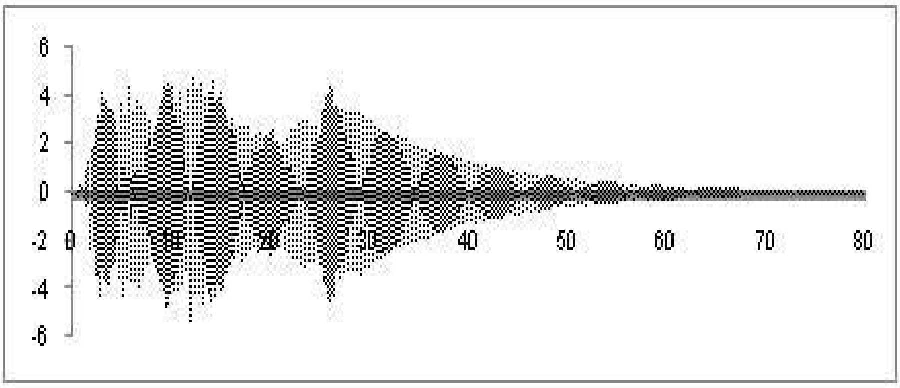


Figure 4.3. Last storey displacement (mm) versus time, equal mass, five storey structure, 3ATMDs on top

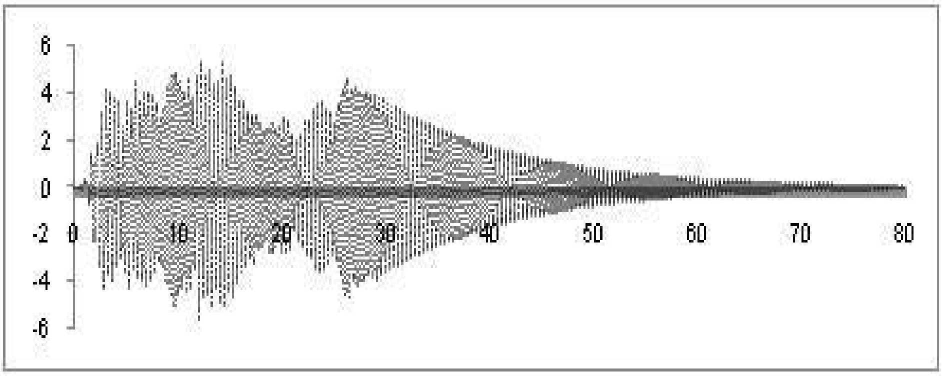


Figure 4.4. Last storey displacement (mm) versus time, non-equal mass, five storey structure, 3ATMDs on top

4.6. Structural Modelling of the fifteen storey structure

In the first case, there is only one ATMD at the top of the structure and the mass of this damper is 2% of the sum of the total structures mass, the critical damping is 0.02 of the critical damping of the structure. The active control procedure is performed by only one Fuzzy Logic controller and the active control device is on the last floor. The fuzzy membership functions and rules are discussed above. The structure is exposed to El Centro earthquake, normalized to 0.5g. The response of the structure due to these external vibrations and the vibration suppression due to the active control device is shown in the figures below.

Table 4-5- Structural characteristics of the sole ATMD, fifteen storey structure

m_{t1}(kgr)	106000
K_{t1}(kN/m)	260
C_{t1}(kNs/m)	400000

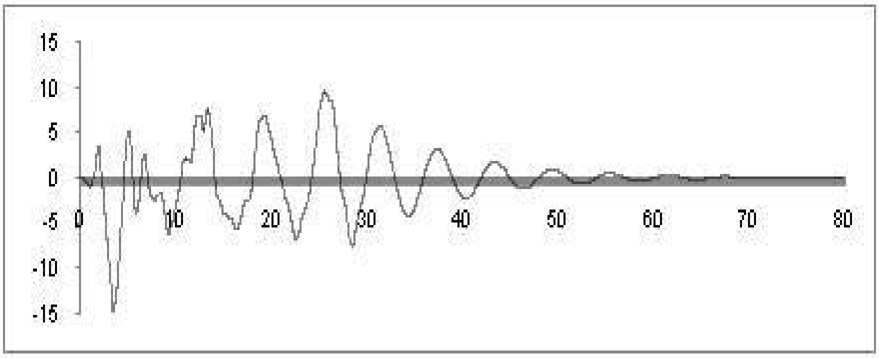


Figure 4.5. Last storey displacement (mm) versus time with a sole ATMD on top, fifteen storey structure

In the second case, there are three ATMDs at the top of the structure and the sum of the mass of these dampers is 2% of the sum of the total structures mass, the critical damping is 0.02 of the critical damping of the structure. The active control procedure is performed by only one Fuzzy Logic controller and the active control device is on the last floor. The fuzzy membership functions and rules are discussed above. The frequency space (β) is 0.25. This case is divided into two sub cases. In the first sub case, the mass of the AMTMDs is equal and in the second sub case, the damping and stiffness of the AMTMDs are equal. The structural characteristics of the AMTMDs for the two cases and the two sub cases are listed in the table below.

Table 4-6- Structural characteristics of the 3TMDs, fifteen storey structure, equal mass

m_{t1}(kgr)	35000
m_{t2}(kgr)	35000
m_{t3}(kgr)	35000
K_{t1}(kN/m)	53000
K_{t2}(kN/m)	70000
K_{t3}(kN/m)	88000
C_{t1}(kNs/m)	34
C_{t2}(kNs/m)	44
C_{t3}(kNs/m)	56

Table 4-7- Structural characteristics of the 3TMDs, fifteen storey structure, non-equal mass

m_{t1}(kgr)	45000
m_{t2}(kgr)	34000
m_{t3}(kgr)	27000
K_{t1}(kN/m)	135000
K_{t2}(kN/m)	135000
K_{t3}(kN/m)	135000
C_{t1}(kNs/m)	86
C_{t2}(kNs/m)	86
C_{t3}(kNs/m)	86

The last storey displacement for the fifteen storey structure with AMTMDs on top, with equal mass is shown in figure 4.5. The last storey displacement for the fifteen storey structure with AMTMDs on top, with non-equal mass is shown in figure 4.6.

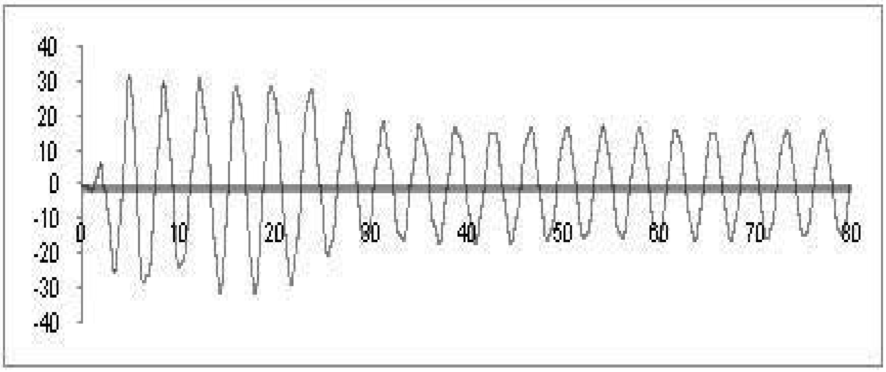


Figure 4.6. Last storey displacement (mm) versus time, equal mass, fifteen storey structure, 3ATMDs on top

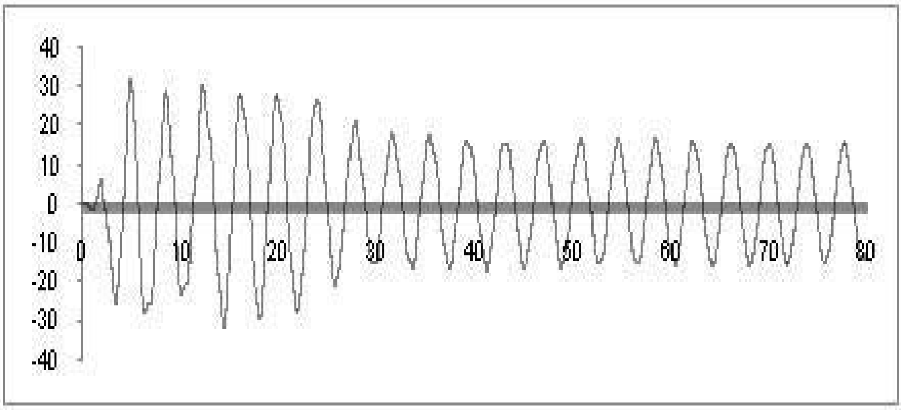


Figure 4.7. Last storey displacement (mm) versus time, non-equal mass, fifteen storey structure, 3ATMDs on top

The maximum displacements of the last storey for the five and fifteen storey structure are shown in table 4-8.

Table 4-8- Maximum displacement (mm) of the last storey for the five and fifteen storey structures

	Five storey	Fifteen storey
	$x_{5)max}$	$x_{15)max}$
1ATMD	6	20
3ATMDs, equal mass	5	30
3ATMDs, non-equal mass	6	30

4.7. Conclusion

Multiple ATMDs have a higher capability in mitigating the vibration induced in the structure due to earthquake excitation since they cover a wider range of frequencies compared to sole

ATMDs. AMTMDs have a more compact volume; this is because sum of the mass of the AMTMD is the mass ratio (= mass of ATMD / mass of entire structure) in contrast to ATMDs.

As observed in this chapter, for the five storey structure, when 3ATMDs with equal mass are installed at the top of the structure, the reduction in the last storey displacement is more considerable compared to 3ATMDs with non-equal mass or a sole ATMD on the top floor. After the earthquake, for the free-vibration period, the 3ATMDs with equal mass have the same effect on the vibration reduction of the last storey.

As the height of the structure is increased to fifteen stories, a sole ATMD on top has considerable effect on the reduction of the last storey displacement. The effect of 3ATMDs with equal mass or non-equal mass on seismic vibration reduction is not observable. Therefore multiple ATMDs are mainly effective in low-rise structures in contrast to a sole ATMD which is very effective in high rise structures.

CHAPTER 5

SELF-ORGANISING ADAPTIVE FUZZY LOGIC CONTROL FOR NON-AFFINE NONLINEAR SYSTEMS

5.1. Introduction

Adaptive fuzzy logic control (Alata, Su & Demirli 2001; Chai & Tong 1999; Cho, Yee & Park 1999; Ge et al. 2010; Han, Su & Stepanenko 2001; Islam & Liu 2011; J.T. Spooner 2001b; Phan & Gale 2007; Rubaai 1999; Wang, Liu & Lin 2002; Wang 1994) have fixed structures after the user has defined the membership functions by trial and error. Due to not having knowledge on the mathematical modelling for different plants, this trial and error takes considerable time. Therefore, self-organising adaptive fuzzy logic controllers are proposed as it does not have a fixed structure and can change and structure itself as it can automatically add and remove membership functions and therefore rules from the fuzzy inference system.

Self-organising adaptive fuzzy logic controllers (Gao & Er 2003; Park, Park, et al. 2005b; Phan & Gale 2008; Qi & Brdys 2009) do not date back to more than a decade. Park (Park, Park, et al. 2005b) propose a self-structuring adaptive fuzzy logic controllers wherein membership functions and therefore rules are added or replaced to the input space. Gao and Er (2003) proposed a self-organizing fuzzy neural system, in which the rule generation criteria was based on the system error and the ε-completeness, and for rule pruning an error reduction ratio was defined. In (Phan & Gale 2008), a self-structuring adaptive fuzzy logic controller is defined particularly for affine nonlinear systems which defines a simple flowchart algorithm to add or replace rules based on two criteria defined; the tracking error and the ε-completeness. Qi and Brdys (2009)proposed a self-organising fuzzy logic controller for affine, nonlinear discrete systems taking advantage of online subtractive clustering and recursive least square methods.

5.2. Affine state space equations versus non-affine state space equations

The contributions mentioned above are only applicable for affine state space equations, as presented below:

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = x_3$$
$$\cdots$$
$$\cdots$$
$$\dot{x}_n = f(x) + g(x)u$$
$$y = x_1; \tag{5.1}$$

where $x = (x_1 \quad x_2 \quad x_3 \quad \cdots \quad x_5)^T$ represents the state vector defined by the user, y is the output vector, and u is the input control.

The aforementioned contribution is further improved by (Phan & Gale 2008) to self-organising adaptive fuzzy logic control of non-affine state space equations presented below:

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = x_3$$
$$\cdots$$
$$\cdots$$
$$\dot{x}_n = f(x, u)$$
$$y = x_1. \tag{5.2}$$

Non-affine nonlinear state space equations have been very challenging to tackle over the passing decade. Park (2005a) has proposed online self-structuring adaptive fuzzy logic control to overcome this challenge. The setback encountered in non-affine nonlinear systems is not having the control input explicitly seen in the state space equations, therefore the popular feedback linearization scheme could not be used. In (Park & Park 2003), the non-affinity in the state space equations is turned into affine as a result of using the Taylor series. In (Du, Shao & Yao 2006), the Nussbaum-Gain and the mean value method is considered to deal with the non-affinity in the state space equations. (Ge et al. 2010),(Essounbouli & Hamzaoui 2006) considered using the mean value method and the implicit function procedure to deal with the control feedback not being visible in the state space equations. In (Park, Park, et al. 2005a),(Calise, Hovakimyan & Idan 2001; Park, Huh, et al. 2005) pseudo-control method is considered in which the pseudo-error needs to be reduced using an adaptive neural network as the output. Liu et al (Liu, Tong & Li 2010) proposed an adaptive neural network method for multi-input multi-output feedback systems by taking into account the mean value and the implicit function method to deal with the non-affinity.

Not only the ideal control needs to be defined, restrictions need to be made on the control gain $\frac{\partial f(x,u)}{\partial u}$. On one hand, the condition for controllability needs to be satisfied $\frac{\partial f(x,u)}{\partial u} > 0$, on the other hand a lower bound g_L needs to be defined in which $\frac{\partial f(x,u)}{\partial u} > g_L > 0$ (Castro 1995) or a design parameter $c$needs to be considered in which $c > \frac{1}{2}\left(\frac{\partial f(x,u)}{\partial u}\right)$. (Park, Park, et al. 2005a),(Calise, Hovakimyan & Idan 2001; Park, Huh, et al. 2005). Other researchers(Ge et al. 2010),(Essounbouli & Hamzaoui 2006) proposed that $\frac{\partial f(x,u)}{\partial u}$ needs to be bounded and a design parameter $k_v$needs to be defined in which $k_v > k_0$, k_0 being the unknown positive constant. For single-input single-output systems, Liu (Liu, Tong & Li 2010) defined a series of design parameters $c_k \geq \frac{2(\bar{g}_{k-1})^2}{c_{k-1}\underline{g}_{k-1}\underline{g}_k}$, in which $k = 2, \dots, n$, n being the order of the system, $\bar{g}_k$ and $\underline{g}_k$ being the higher and lower bounds for the control gains.

The conditions defined above indicate the complex characteristics of the controllers in non-affine case compared to affine case (Chai & Tong 1999; Cho, Yee & Park 1999; Rubaai 1999; Wang, Liu & Lin 2002). Therefore to deal with these setbacks several methods are presented. In the first step, the ideal control needs to be defined, the implicit function method is used similar to (Ge et al. 2010),(Essounbouli & Hamzaoui 2006),(Liu, Tong & Li 2010). In the second step, the system stability needs to be checked, wherein the universal approximation theory is introduced. This method is simple as extra mathematical equations only involve in the stability check, therefore there is no restriction for the control gain. The controller is the same for both cases, affine and non-affine state space equations making this method more efficient. In this chapter, the adaptive fuzzy logic system is defined and the self-organising process is introduced. Section 3, discusses the application of this defined adaptive fuzzy system in the control of affine nonlinear state space equations. Section 4, the universal approximation method is considered to make the stability check similar to the affine case. In section 5, some examples are provided to discuss the aforementioned method in practice. In the end, discussions and conclusion are presented in section 6.

5.3. Self- organisingAdaptive fuzzy system description

5.3.1. Description of Fuzzy systems

The zero order *Takagi-Sugeno* fuzzy systems are used in which the point *fuzzification* procedure, product-type inference and centre-average *defuzzifier* is considered as the fuzzy inference parameters.

For each $a, b \in R$, $a < b$, the $\alpha(a, b): R \to [0,1]$ is considered a membership function in which $\alpha(a, b)(x) \neq 0$ if $x \in (a, b)$ and $\alpha(a, b)(x) = 0$ if $x \notin (a, b)$.

The fuzzy system assumed here has the below **If-Then** rule:

$$R^{(i)}: IF\ x_1 is\ A_1{}^i, and\ x_2 is\ A_2{}^i, and\ \ldots\ and\ x_n is\ A_n{}^i,$$
$$THEN\ y\ is\ \theta_i;$$

where $x = (x_1, x_2, \ldots, x_n)^T \epsilon U \subset R^n$ and $y \in V \subset R$ are the input and output considered for the fuzzy system. The membership functions are shown as $A^i{}_j$ and are defined as $A^i{}_j(x_j) = \alpha(a^i{}_{j1}, a^i{}_{j2})(x_j)$ considering $a^i{}_{j1} < a^i{}_{j2}$, $i = 1, \ldots, M$ in which M is defined as the number of rules, $j = 1, \ldots, n$. The system output corresponding to rule $R^{(i)}$ is θ_i.

In the end, the output for this fuzzy system is in the below form:

$$\hat{y} = \hat{f}(x|\theta) = \frac{\sum_{i=1}^{M} \theta_i \mu_i(x)}{\sum_{i=1}^{M} \mu_i(x)} = \sum_{i=1}^{M} \theta_i\, \zeta_i(x); \tag{5.3}$$

where $\mu_i(x) = \prod_{j=1}^{n} A^i{}_j(x_j)$, $\zeta_i(x) \geq 0\ \ and\ \ \sum_{i=1}^{M} \zeta_i(x) = 1$.

This fuzzy logic system is assumed to have universal approximation characteristics in which a fuzzy system is considered to approximate any continuous function (Ge et al. 2010; J.T. Spooner 2001a; Wang 1994), (Castro 1995; Kosko 1994; Zeng & Singh 1994).

5.3.2. Self-organisingAlgorithm

Triangular membership functions are used as they are the simplest form of membership functions. The self-organising algorithm is presented in figure 5.1.

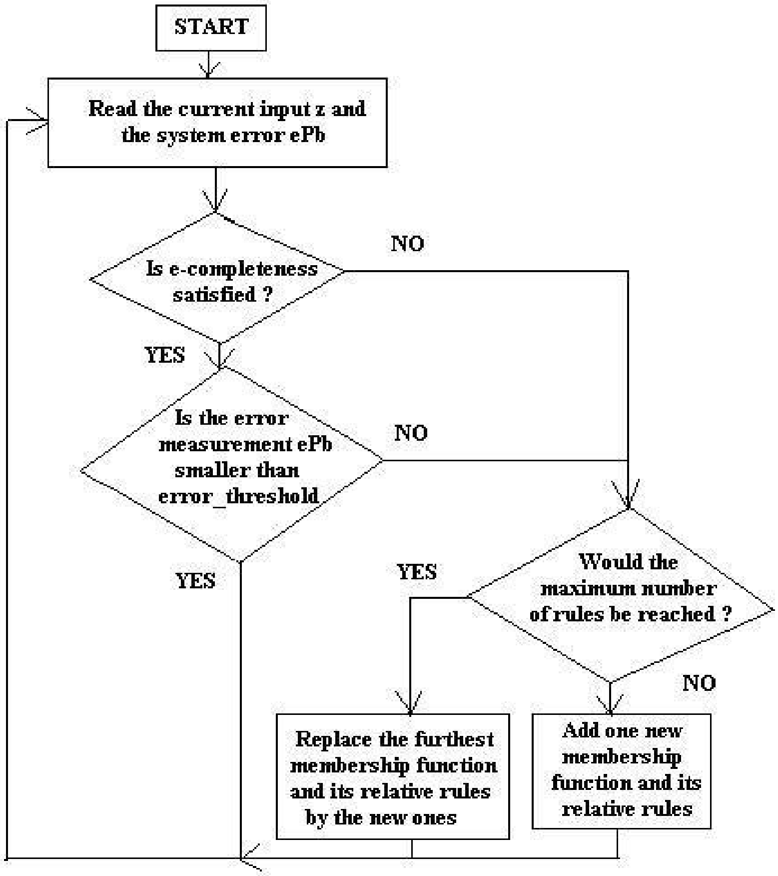


Figure 5.1. Self-organising algorithm flowchart

a) Assumed criteria for rule production

The two criteria considered for rule production are tracking error (system error) and ε-completeness:

- Tracking error (system error):

Tracking error or system error is the difference between the desired output defined by the user and the fuzzy system output. A parameter *error_threshold* is defined in which if the system error exceeds this parameter a new membership function is added to the input with the highest number of fired membership functions.

- The $\varepsilon -$ completeness:

This criteria is satisfied if for any input there is a membership function in which the membership degree does not exceed ε_0. Therefore, $\varepsilon = {\varepsilon_0}^n$, n being the number of inputs. If there exists a membership degree exceeding ε_0, a new membership function will therefore be added to the input.

b) The parameters of the added membership functions need to be determined

The centre of the newly added membership function is considered to be the value of the input variable. The centre of the left and right adjacent membership functions are the left and right points of this new membership function. Therefore, the adjacent membership functions are defined to satisfy the ε-completeness criteria. Other design parameters are defined; $max\_mf\_distance$ and $min\_mf\_distance$ in case there is no adjacent membership function. In which the left (or right) point of the newly added membership is determined to have a centre distance equivalent to $max\_mf\_distance$; a value defined by the user. In some cases, membership functions become too close to each other, when the centre distance of the newly added membership functions and the centre of the adjacent membership functions exceed $min\_mf\_distance$, a value defined by the user.

c) The added rules are determined

By adding a new membership function, 2^{n-1} new rules will automatically be added to the rule base, n being the number of inputs. The newly added rules will be produced in addition to their consequences adding to the fuzzy system output.

d) Deleting an existing membership function

By adding a new membership function, the new number of rules must not exceed B_{rule}. If exceeded, the furthest membership function must be deleted, taking all its relevant rules with it.

5.4. Self-organising adaptive fuzzy logic control for Affine nonlinear systems

An adaptive fuzzy logic controller for a single-input single-output system in affine nonlinear systems is shown in the state space format presented in the equation below:

$$
\begin{gathered}
\dot{x_1} = x_2 \\
\dot{x_2} = x_3 \\
\cdots \\
\cdots \\
\dot{x_n} = f(x) + g(x) \qquad (5.4) \\
y = x_1\,;
\end{gathered}
$$

where u is the control input; y is the system output; $f(x)$ and $g(x)$ are unknown continuous functions; and $x = (x_1, x_2, \ldots, x_n)^T$ is the state vector of the system.

Assumption 5.1: $g(x)$ is considered to be continuous with a known sign in $x \in \Omega_x$, Ω_x being the controllability zone.

As the controllability condition in equation (5.3) implies $g(x) \neq 0$ and $g(x)$ being continuous for the controllability region, with the assumption of $g(x) > 0$ for this entire region.

The control objective is defining a self-organising adaptive fuzzy logic controller in which the output $y(t)$ is tracking a desired reference $r(t) \in C^m$.

Considering known functions for $f(x)$ and $g(x)$, the *ideal control signal* is defined below:

$$u^* = \frac{1}{g(x)}(-f(x) + k^T e + r^{(n)}); \tag{5.5}$$

where $e = (e, \dot{e}, \ddot{e}, \ldots, e^{(n-1)})^T, e = r - y, k = (k_1, k_2, \ldots, k_n)^T$. By substitution of equation (5.3) the error function is transformed into the below form:

$$e^{(n)} = -k^T e = -k_1 e - k_2 \dot{e} - \cdots - k_n e^{(n-1)}; \tag{5.6}$$

k is chosen in a way to satisfy the Hurwitz stability of equation (5.6) in which the error is reduced to zero as time exceeds infinity or in other words the output tracks the desired output. Therefore, the objective of the control is met.

It is assumed that $v = k^T e + r^{(n)}$. Equation (5.5) turns into the below format:

$$u^* = \frac{1}{g(x)}\left(-f(x) + k^T e + r^{(n)}\right) = \frac{1}{g(x)}(-f(x) + v) = u^*(X); \tag{5.7}$$

where $= (x^T, v)^T \in \Omega_X$, $\Omega_X = \left\{X \middle| x \epsilon \Omega_x, \| r \| \leq r_0, \| r^{(n)} \| \leq r_1\right\}$.

Assuming $f(x)$ and $g(x)$ as unknown functions, the fuzzy logic controller in equation (5.3) is used to approximate $u^*(X)$ as shown below:

$$u = \hat{u}(X|\theta) = \sum_j \theta_j \zeta_j(X) . \tag{5.8}$$

Assumption 5.2 The upper bound for the rule generation B_{rule} is selected so the controller would not be capable of exceeding the suitable size in the fuzzy inference system. In addition, this assumption is more flexible compared to fixed adaptive fuzzy logic controllers where the main objective is to define a fuzzy rule base satisfying the desirable approximation. Assuming the upper bound for the required number of rules B_{rule} , the self-organising algorithm will automatically produce the fuzzy inference system.

The adaptive parameter vector for the final fuzzy logic controller is considered to be $\theta = (\theta_1, \theta_2, \dots, \theta_N)^T$ in which $N \leq B_{rule}$.

Therefore $\theta = (\theta^T{}_{ac}\ \ \theta^T{}_{in})^T$, where $\theta_{ac} = (\theta_1, \theta_2, \dots, \theta_M)^T$, $(M \leq N)$ are the active parameters in the vector of adaptive parameters, and $\theta_{in} = (\theta_{M+1}, \theta_{M+2}, \dots, \theta_N)^T$ are the inactivated parameters which do not interfere in the controller design process. Therefore, the output of the controller is in the form below:

$$u = \hat{u}(X|\theta_{ac}) = \sum_{j=1}^{M} \theta_j\, \zeta_j(X). \tag{5.9}$$

Assumption 5.3 The ideal control needs to be bounded into lower and higher bounds as shown below:

$$u_L \leq u^*(X) \leq u_U\,, \forall X \in \Omega_x\,.$$

Therefore, an actuator that can satisfy the above conditions is required. Based on this assumption, the boundedness of the adaptive parameters is satisfied.

By substituting the controller output with $\hat{u} = \hat{u}(X|\theta_{ac}) = \sum_{j=1}^{M} \theta_j\, \zeta_j(X)$ and adding and subtracting $g(x)u^*(X)$ to equation (5.3), the equation for error dynamics is achieved below:

$$e^{(n)} = -k^T e + [g(x)u^*(X) - g(x)\hat{u}(X|\theta_{ac})]. \tag{5.10}$$

Lemma 1. Assuming $\varepsilon^* > 0$, $\zeta(X)$ can be presented in the vector form of $\zeta(X) = (\zeta_1(X), \zeta_2(X), \dots, \zeta_M(X))^T$ in addition to assuming an ideal parameter vector $\theta^* = (\theta^*{}_1, \theta^*{}_2, \dots, \theta^*{}_M)^T$ where:

$$g(x)u^*(X) - g(x)\hat{u}(X|\theta_{ac}) = \sum_{j=1}^{M} c^j\,(\theta^*{}_j - \theta_j)\zeta_j(X) + \varepsilon; \tag{5.11}$$

where $|\varepsilon| \leq \varepsilon^*$ and c^j are positive values.

Proof

The lemma above is proven in (Phan & Gale 2006, 2008). The following sections discuss the extended form of this lemma, in addition to the proof provided in appendix A.

When lemma 1 is applied to equation (5.10), the error dynamic is resulted in the format below:

$$e^{(n)} = -k^T e + [\sum_{j=1}^{M} c^j\,(\theta^*{}_j - \theta_j)\zeta_j(X) + \varepsilon]\,.$$

The vector format is presented below:

$$\dot{e} = \Lambda_C e + b_C [\sum_{j=1}^{M} c^j (\theta^*{}_j - \theta_j) \zeta_j(X) + \varepsilon]; \tag{5.12}$$

where

$$\Lambda_C = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \\ -k_1 & -k_2 & -k_3 & \cdots & -k_n \end{bmatrix}, b_C = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix};$$

where Λ_C is a stable matrix and a positive definite symmetric $n \times n$ matrix Q is assumed in which the Lyapunov function below needs to be satisfied:

$$\Lambda^T{}_C P + P\Lambda_C = -Q; \tag{5.13}$$

where P is derived from the function above and is a positive definite matrix.

Remark 1 The error dynamic equation (5.12) is very popular in adaptive intelligent control. Therefore, for the stability check, lemma 1 is presented. In the following discussions in section 3, the extended form of this lemma to change the error dynamics for non-affine systems to the format in equation (5.12) is presented.

Theorem 1 Based on system (5.4) and the assumptions discussed above, the controller in equation (5.9) and the self-organising adaptive fuzzy logic control algorithm in section 2, the adaptive law is defined as below:

$$\dot{\theta}_j = \begin{bmatrix} & \gamma e^T P b_C \zeta_j(X) \quad if(u_L < \theta_j < u_U) \\ & or(\theta_j = u_U \; and \; \gamma e^T P b_C \zeta_j(X) < 0) \\ 0 & or(\theta_j = u_L \; and \; \gamma e^T P b_C \zeta_j(X) > 0); \\ & or(\theta_j = u_U \; and \; \gamma e^T P b_C \zeta_j(X) \geq 0) \\ & or(\theta_j = u_L \; and \; \gamma e^T P b_C \zeta_j(X) \leq 0) \end{bmatrix} \tag{5.14}$$

where the adaptive parameters and the tracking error need to be bounded as shown below:

$$u_L \leq \theta_j \leq u_U, j = 1 \dots M \tag{5.15}$$

$$\| e(t) \| \leq \sqrt{\frac{2max\{V(0), \frac{c}{\propto}\}}{\lambda_{min}(P)}} \quad , \forall t > 0 \; ; \tag{5.16}$$

where $\alpha = \frac{(\lambda_{min}(Q)-1)}{\lambda_{max}(P)}$, $V(0)$ is assumed based on the initial conditions and is required to be positive, and c being a positive value used in tuning the adaptive parameter γ.

The control system needs to be uniformly ultimately bounded (UUB), in which the error function is a compact set as defined below:

$$\Omega_{\underline{e}} = \left\{ e(t) \middle| \parallel e(t) \parallel \leq \sqrt{\frac{\parallel P b_C \parallel^2 \parallel \varepsilon^* \parallel^2}{\lambda_{min}(Q) - 1}} \right\}. \tag{5.17}$$

Proof:

The proof is presented in (Phan & Gale 2008).

5.5. Self-organising adaptive fuzzy logic control for Non-affine nonlinear systems

The state space equations for a single-input single-output system taking into account nonlinearity and non-affinity is presented in the equations below:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= x_3 \\ &\cdots \\ &\cdots \\ \dot{x}_n &= f(x, u) \\ y &= x_1\,; \end{aligned} \tag{5.18}$$

where $u \epsilon R$ is the input control, $y \epsilon R$ is the output, $f(x, u)$ being the non-affinity format of this state space equation as a nonlinear continuous function which is unknown, $x = (x_1, x_2, \dots, x_n)^T$ is the state vector of this system.

The control objective is the same as the affine case:

Control objective is designing a fuzzy logic controller which is adaptive in which the closed loop system is stable in which the variables are obliged to be bounded. The output $y(t)$ has to track the reference signal $r(t) \epsilon C^n$.

Assumption 5.4: The controllability of the non-affine nonlinear function needs to be checked:

$$\frac{\partial f(x,u)}{\partial u} > 0\,; \tag{5.19}$$

where $(x, u) \epsilon \Omega_x \times R$ belongs to the controllability region Ω_x .

Assumption 5.5 The upper bound for the rules B_{rule} needs to be defined so the fuzzy inference size does not exceed a certain specific value.

Assumption 5.6 The bounds for the ideal control signal needs to be determined:

$$u_L \leq u^*(X) \leq u_U\ , \forall X \epsilon \Omega_X\ .$$

In contrast to the affine state space equations, the explicit form of the *ideal control signal* is not available in the state space equation. Therefore, the implicit function theorem is considered to present the ideal control law as discussed below:

1) Ideal control law is presented:

Considering $e = r - y$, $e = (e, \dot{e}, \ddot{e}, \dots, e^{(n-1)})^T$, and $k = (k_1, k_2, \dots, k_n)^T$ in which the Hurwitz stability of the polynomial $s^n + k_n s^{n-1} + \cdots + k_1$ is satisfied. The ideal control law is presented in the form below:

$$e^{(n)} = -k^T e = -k_1 e - k_2 \dot{e} - \cdots - k_n e^{(n-1)}\ ;$$

in which the tracking error is expected to reach zero.

Assume:

$$v = r^{(n)} + k^T e. \tag{5.20}$$

In order to have the non-affinity in the ideal control law, v needs to be added and subtracted to equation (5.18) resulting in the equation below:

$$e^{(n)} = -k^T e - f(x, u) + v; \tag{5.21}$$

in which an ideal control signal $u^*(x, v)$is established as below:

$$f(x, u^*(x, v)) = v \quad \text{for} \quad (x, v) \in R^n \times R\ .$$

Lemma 2. This lemma was previously introduced in lemma 2.8 as the proof is presented in (Ge et al. 2010), in which f is a continuously differentiable function $f{:}\,R^n \times R \to R$ and is bounded by a positive constant q in which $\| \frac{\partial}{\partial u} f(x, u) \| > q > 0$ for all $(x, u) \in R^n \times R$. Therefore a continuous function $g{:}\,R^n \to R$ exists wherein $f(x, g(x)) = 0$.

Proof is presented in (Ge et al. 2010).

Assuming $X = (x, v) \in R^{n+1}$ and $F(X, u) = f(x, u) - v$.

in which

$\frac{\partial F(X,u)}{\partial u} = \frac{\partial f(x,u)}{\partial u} - \frac{\partial v}{\partial u} > 0$ as $\frac{\partial v}{\partial u} = 0$ and $\frac{\partial f(x,u)}{\partial u} > 0$ (assumption 1).

Therefore, lemma 1 is applied for $F(X, u)$ in which a continuous function $u^*(X)$ exists so that $F(X, u^*(X)) = 0$ or:

$$f(x, u^*(X)) = v. \tag{5.22}$$

2) The stability needs to be checked

The stability of the control system is confirmed if the error dynamics in equation (5.21) is changeable to the standard format in equation (5.12). If this condition is satisfied, the controller presented in theorem 1 is approved to have close-loop stability.

Based on equation (5.21) and (5.22), the error dynamics is presented below:

$$e^{(n)} = -k^T e + [f(x, u^*(X)) - f(x, u(X))]. \tag{5.23}$$

The same as discussed in section 2, considering the adaptive parameters as $\theta = (\theta^T{}_{ac}\theta^T{}_{in})^T = (\theta_1, \theta_2, .., \theta_N)^T$ for the final fuzzy logic controller, in which the activated adaptive parameters need to be defined. A fuzzy logic system as discussed in section 2 to approximate $u^*(X)$ is defined below:

$$u(X) = \hat{u}(X|\theta_{ac}) = \sum_{j=1}^{M} \theta_j \, \zeta_j(X). \tag{5.24}$$

The universal approximation method, as discussed in the previous sections, is used to indicate the existence of a fuzzy logic controller with the format shown in equation (5.24) to predict an ideal control signal approximating the fuzzy controller output.

Lemma 3. Assume $\varepsilon^* > 0$, $\zeta(X) = (\zeta_1(X), \zeta_2(X), \ldots, \zeta_M(X))^T$ is presented. Assuming an ideal parameter vector $\theta^* = (\theta_1, \theta_2, \ldots, \theta_M)^T$ in which:

$$f(x, u^*(X)) - f(x, u(X)) = \sum_{j=1}^{M} c^j \left(\theta^*{}_j - \theta_j\right)\zeta_j(X) + \varepsilon; \tag{5.25}$$

and $|\varepsilon| \leq \varepsilon^*$ and c^j are some positive constants.

Proof

The proof is similar to the proof of the universal approximation method presented in (Castro 1995).

The error dynamics is achieved when the equation (5.25) is substituted into equation (5.23):

$$e^{(n)} = -k^T e + \sum_{j=1}^{M} c^j \left(\theta^*{}_j - \theta_j\right)\zeta_j(X) + \varepsilon. \tag{5.26}$$

As shown below, the vector format of the error dynamics is:

$$\dot{e} = \Lambda_C e + b_C \left[\sum_{j=1}^{M} c^j (\theta^*{}_j - \theta_j)\zeta_j(X) + \varepsilon\right]; \tag{5.27}$$

where

$$\Lambda_C = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \\ -k_1 & -k_2 & -k_3 & \cdots & -k_n \end{bmatrix}, b_C = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}.$$

Equation (5.27) is similar to equation (5.12). Therefore, the error dynamics of a non-affine nonlinear system is transferred to the extended format of the universal approximation error method, as discussed in lemma 6.2. Therefore, the controller presented in theorem 1 promises the closed loop stability of the system.

The following sections present two examples of non-affine nonlinear systems.

5.6. Numerical Examples

1) Example 1

This example depicts the design procedure of a particular system with non-affinity and nonlinearity in the state space equations (Essounbouli & Hamzaoui 2006; Ge et al. 2010; Park, Huh, et al. 2005; Park, Park, et al. 2005a):

$$\dot{x_1} = x_2$$

$$\dot{x_2} = {x_1}^2 + 0.15u^3 + 0.1(1 + {x_2}^2)u + \sin(0.1u)$$

$$y = x_1 . \tag{5.28}$$

The controllability condition needs to be checked $\frac{\partial F(X,u)}{\partial u} > 0$. The initial condition for this system is $x(0) = [0\ 0]^T$. The main objective is to track the output $y(t)$ when a desired reference is defined $r = \sin(t) + \cos(0.5t)$.

The input has been chosen in the below form:

$$x_1 \in [-5,5];\ x_2 \in [-5,5];\ v \in [-5,5] .$$

The parameters of the controller are chosen as below:

$$k = [1 \quad 1]^T, Q = \begin{bmatrix} 20 & 0 \\ 0 & 10 \end{bmatrix}, P = \begin{bmatrix} 25 & 10 \\ 10 & 15 \end{bmatrix}, \gamma = 100, u_L = -25\,, u_U = 25\,.$$

The learning parameters for the adaptive controller are defined as below:

$\varepsilon_0 = 0.5$, $error\_threshold = 5$,

$\min\_mf\_distance = [1 \quad 1 \quad 1]$, $\max\_mf\_distance = [5 \quad 5 \quad 5]$, $B_{rule} = 30$.

In the first step, the fuzzy system has only 1 rule with 1 membership function for each input, as shown in the figure below:

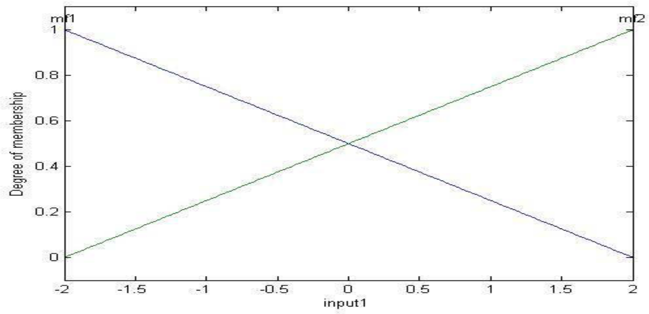


Figure 5.2. Initial membership functions for all input and output variables

As seen in figure 5.3, the controller output $y(t)$ has successfully tracked the desired output $r(t) = \sin(t) + \cos(0.5t)$.

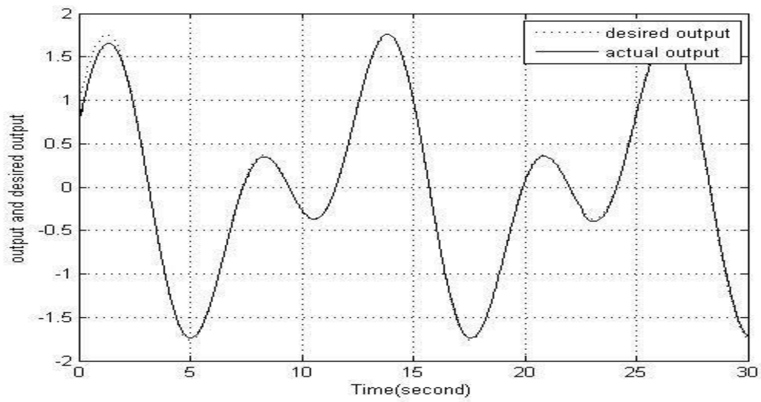


Figure 5.3. Output versus desired output

As shown in figure 5.4, after about 10 seconds the tracking error starts to converge to zero indicating that the output has tracked the desired reference output defined by the user.

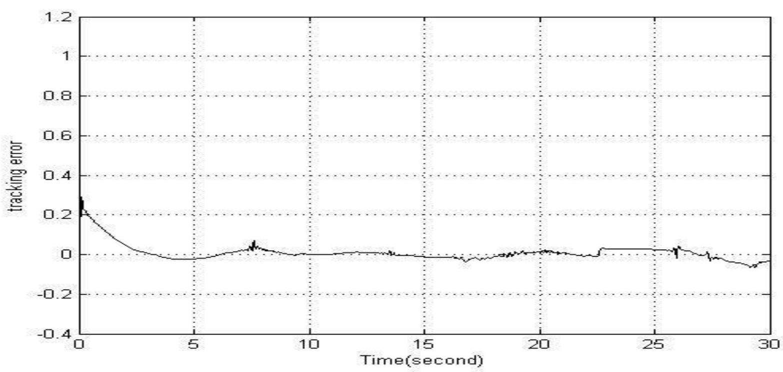


Figure 5.4. Tracking error

The control signal is shown in the figure below:

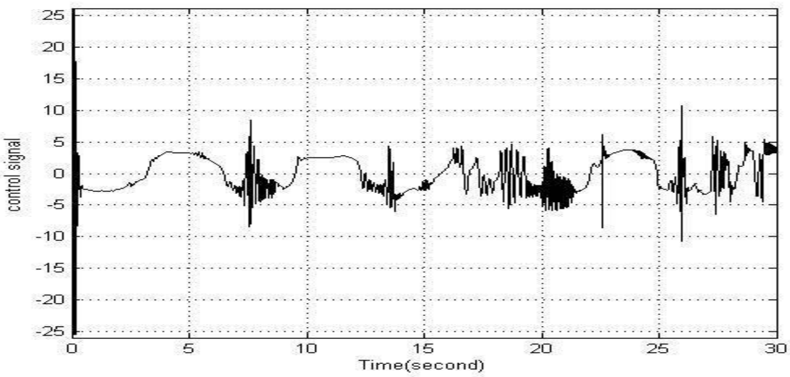


Figure 5.5. Control signal

The chattering problem encountered in this system can be solved by reducing the adaptive gain γ but with this reduction, the tracking error will be increased, therefore a compromise needs to be reached. Self-structuring occurs in the *7th* second where the self-structuring flag changes from *-1* to *1*. Another change has been seen in the *23rd* and *26th* second. As the change of this flag from *1* to *-1* and *-1* to *1* indicates a change has occurred in the controller parameters.

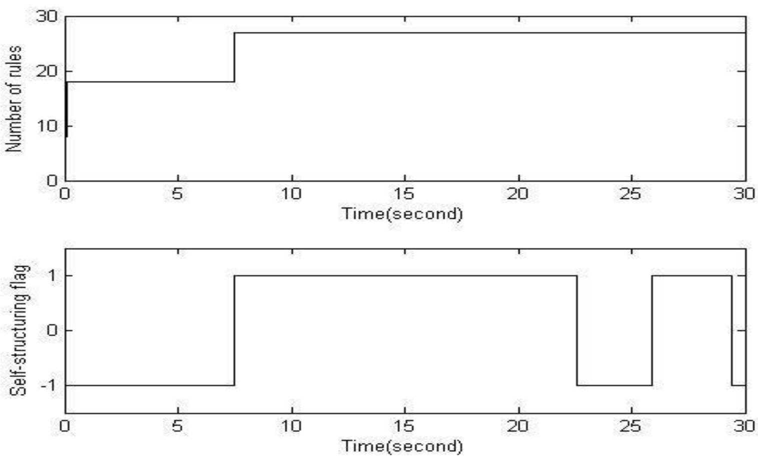


Figure 5.6. Number of rules and self-organising flag

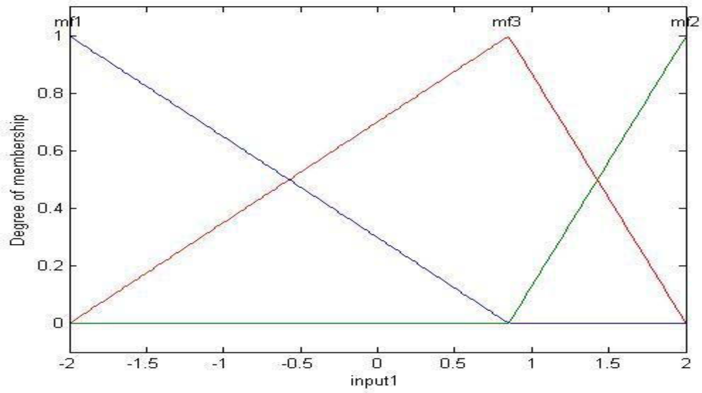


Figure 5.7. Final membership functions for input 1

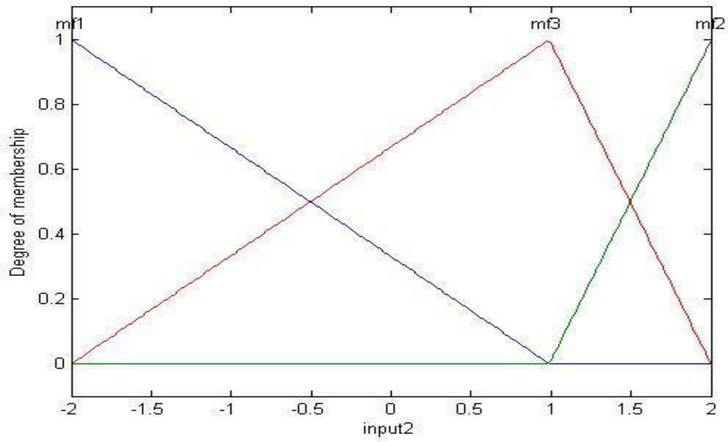


Figure 5.8. Final membership functions for input 2

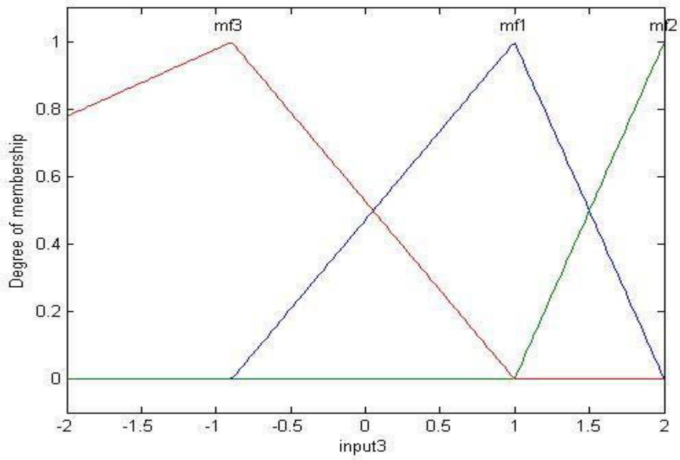


Figure 5.9. Final membership functions for input 3

The final membership functions for the three inputs are also triangular. As can be seen, three membership functions have been defined after the self-organising criteria for the fuzzy logic controller has been met. Therefore, the initial membership functions for the three inputs which are two have been transformed into three as a result of the trial and error adaptation process.

The *error_threshold has* been reduced from *5* to *4*, to observe how the self-structuring adaptive fuzzy logic controller adds and removes rules, and how the rule generation criteria are satisfied. The rule generation criteria are satisfied. The initial membership functions for all the input and output variables are shown in figure 5.10. The output versus desired output is shown in figure 5.11. The tracking error converges zero at the *6th* second, as shown in figure 5.13.

The number of rules remains on *18*, on the *8th* second where the self-organising flag changes from *1* to *-1* and *-1* to *1* on this second, as shown in figure 5.14. Therefore, the self-structuring criteria for the fuzzy logic controller have been met. The final membership functions for the inputs and outputs are shown in the figures below.

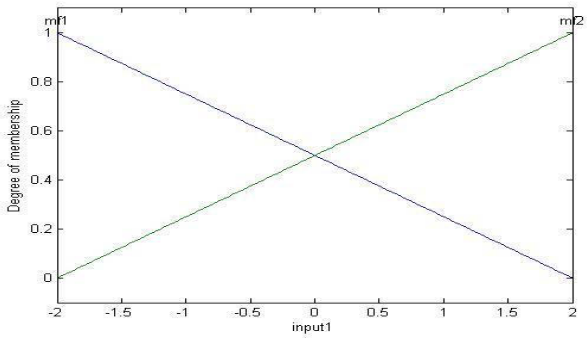


Figure 5.10. Initial membership functions for all input and output variables

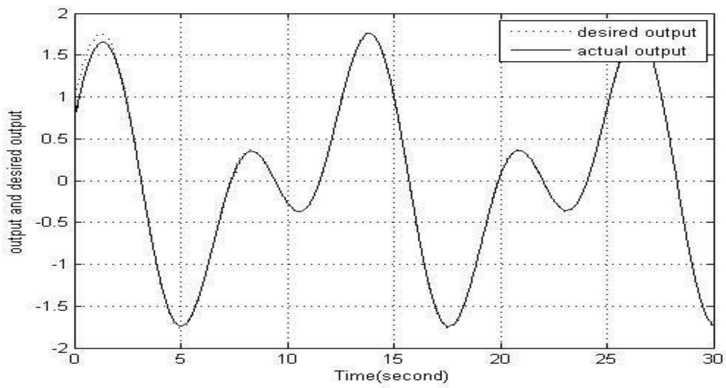


Figure 5.11. Output versus desired output

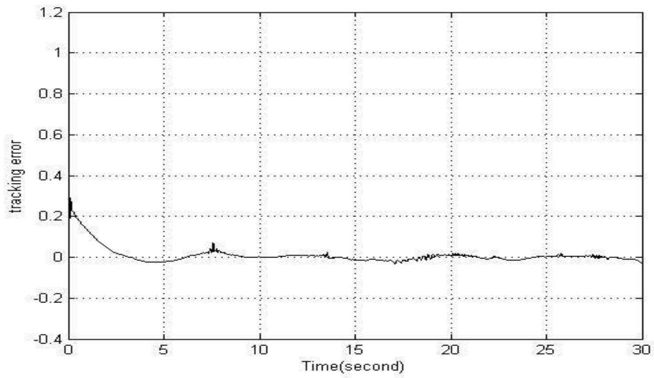


Figure 5.12. Tracking error

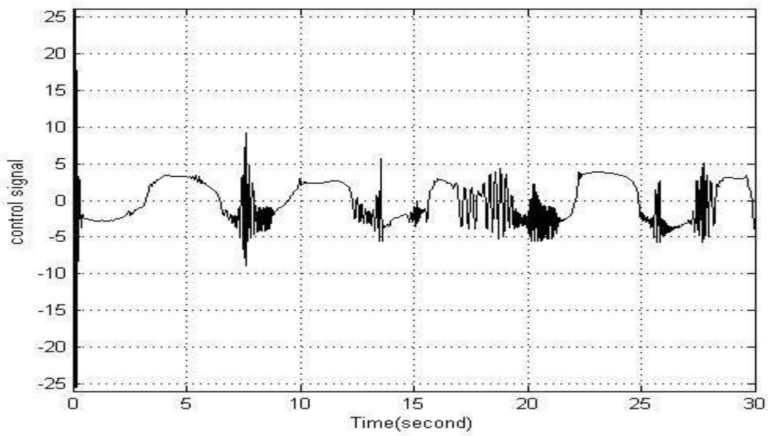


Figure 5.13. Control signal

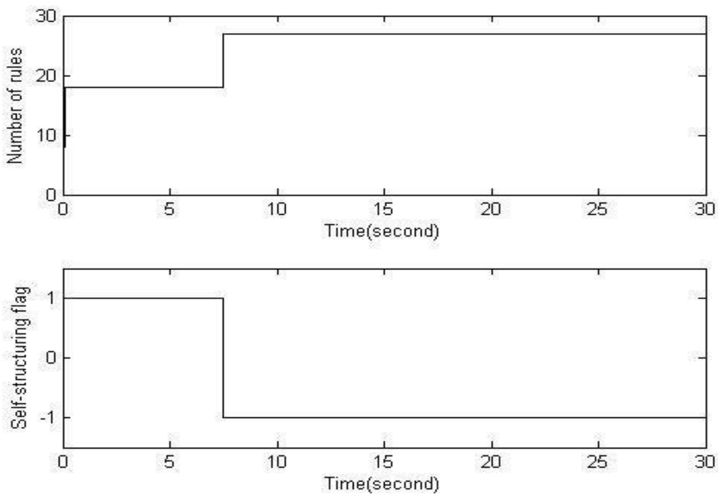


Figure 5.14. Number of rules and self-organising flag

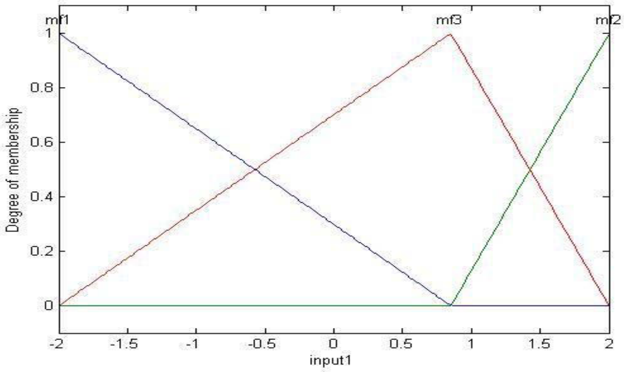


Figure 5.15. Final membership functions for input 1

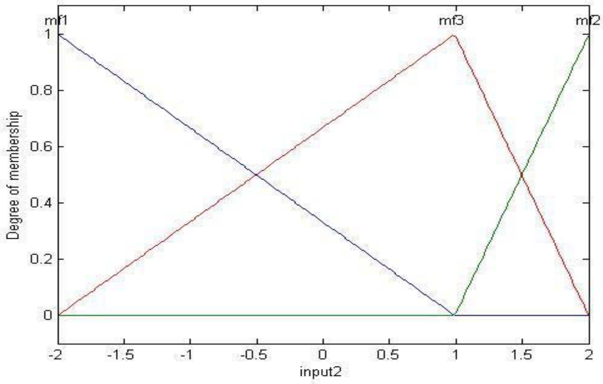


Figure 5.16. Final membership functions for input 2

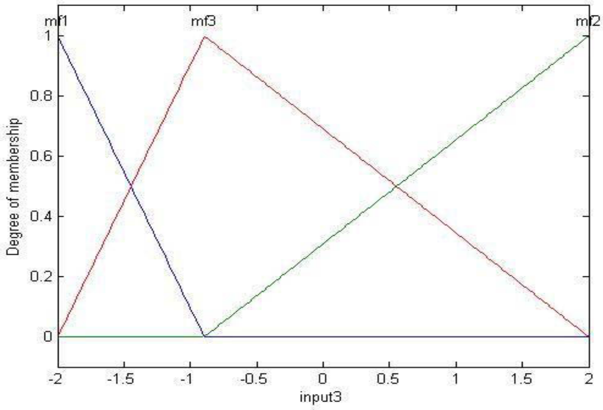


Figure 5.17. Final membership functions for input 3

As can be seen, the initial membership functions for the three inputs are two triangular membership functions for each input. As the self-organising criteria for the fuzzy logic controller has been met, a third membership function is added to each of the inputs. Therefore, reducing the *error_threshold* from *5* to *4*, results in a much quicker convergence rate as the *self-organising flag* only changes once from *1* to *-1*, and the tracking error is reduced from *10* to *6* seconds which also indicates the faster convergence rate.

2) Example 2

Another example of non-affine nonlinear state space equations is presented here(Hovakimyan, Nardi & Calise 2002; Park & Kim 2004) . The system is defined below:

$$\dot{x_1} = x_2$$
$$\dot{x_2} = -x_1 + 2x_2 - 2{x_1}^2 x_2 + \frac{u}{\sqrt{|u| + 0.1}}$$
$$y = x_1 \,. \tag{5.29}$$

The controllability condition needs to be satisfied $\frac{\partial F(X,u)}{\partial u} > 0$. The state space equations in the initial step are $x(0) = [0.3 \quad 0]^T$. The aim of this control is having the output $y(t)$track the desired reference output defined $r(t) = \frac{\pi}{6}\sin(t)$.

The input membership functions have the ranges below:

$$x_1 \in [-2,2];\ x_2 \in [-2,2];\ v \in [-2,2]\,.$$

The parameters of the controller are assumed below:

$$k = [1 \quad 1]^T, Q = \begin{bmatrix} 20 & 0 \\ 0 & 10 \end{bmatrix}, P = \begin{bmatrix} 25 & 10 \\ 10 & 15 \end{bmatrix}, \gamma = 50, u_L = -25\,, u_U = 25\,.$$

The learning parameters for the adaptive controller are assumed below:

$\varepsilon_0 = 0.5$, $error\_threshold = 2$,

$\min\_mf\_distance = [0.4 \quad 0.4 \quad 0.4]$, $\max\_mf\_distance = [2 \quad 2 \quad 2]$, $B_{rule} = 30$.

The membership functions of the fuzzy system in the first step, with 1 membership function for each input is shown in the figure below:

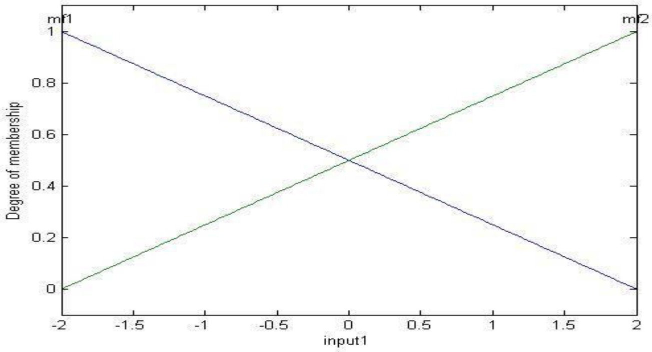


Figure 5.18. Initial membership functions for all input and output variables

The controller in this non-affine nonlinear system has the objective to track the desired reference signal $r(t) = \frac{\pi}{6}\sin(t)$, as shown in figure 5.19 and figure 5.20.

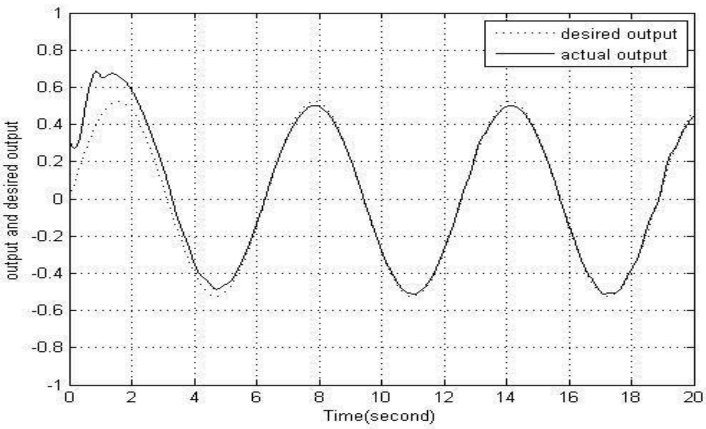


Figure 5.19. Output versus desired output

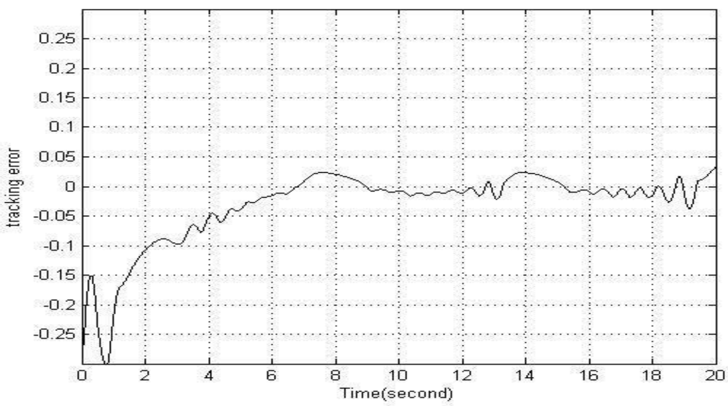


Figure 5.20. Tracking error

The control signal is shown in the figure below:

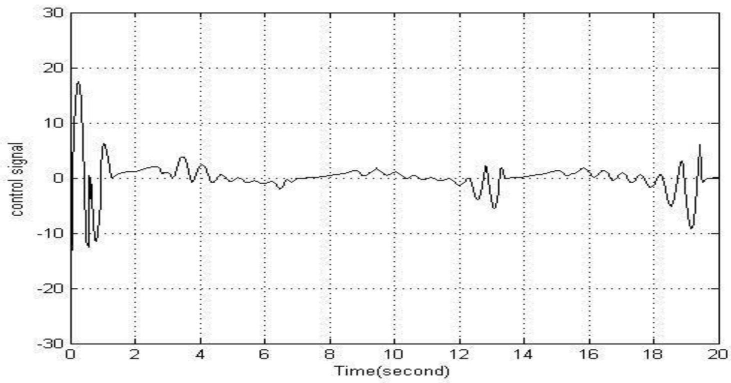


Figure 5.21. Control signal

The number of rules exceeds to *18* and remains constant in the *1*st second and therefore the self-structuring flag changes from *-1* to *1* in this second, as shown in figure 5.22.

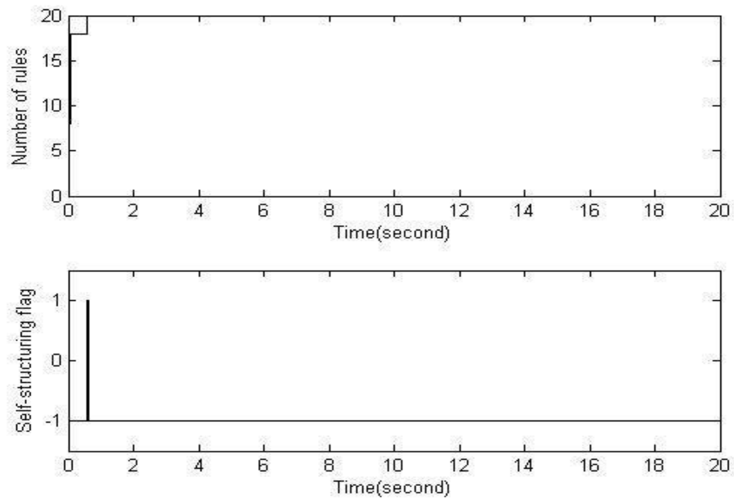


Figure 5.22. Number of rules and self-organising flag

The final membership functions for the inputs are shown in the figures below:

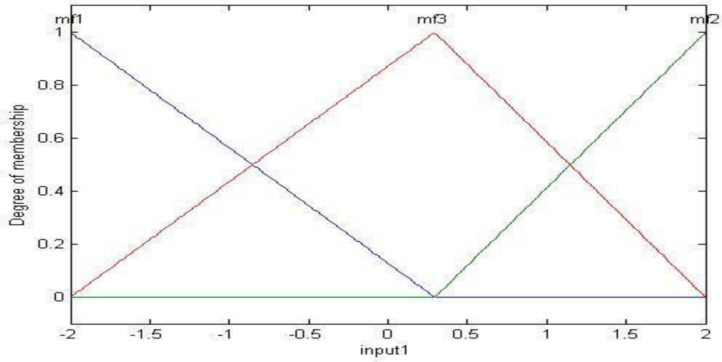


Figure 5.23. Final membership functions for input 1

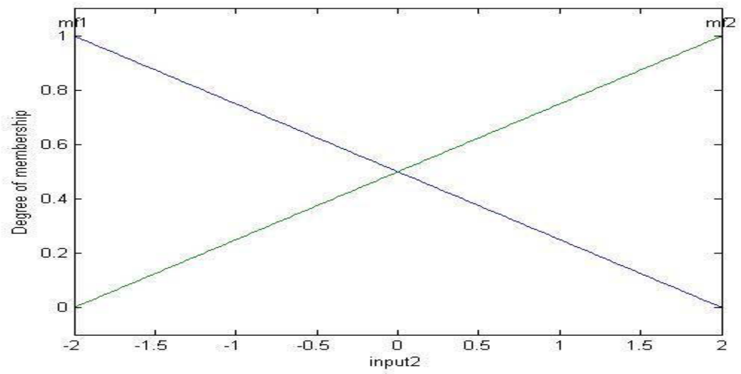


Figure 5.24. Final membership functions for input 2

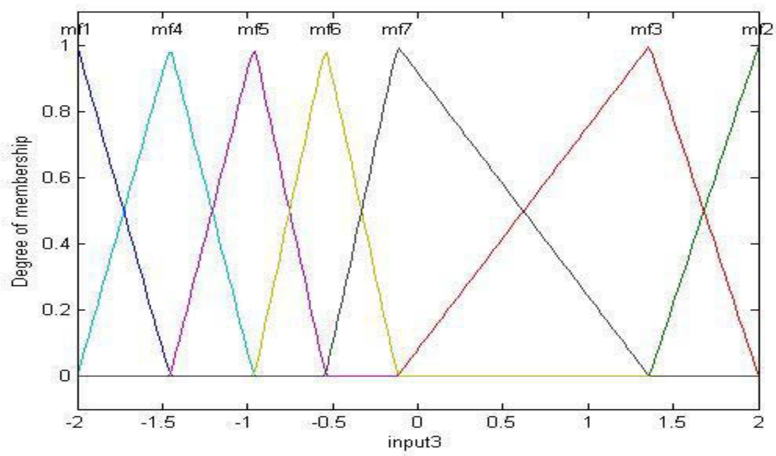


Figure 5.25. Final membership functions for input 3

The initial membership function for the three inputs was two triangular membership functions. As the self-structuring procedure continues the final membership function for each input varies. As can be seen, the final membership function, after the self-structuring criteria for the fuzzy logic control has been met, is increased to seven triangular membership functions. The number of rules has exceeded from 8 to 18 at the start of the iteration and as the *1st* second is approached, the number of rules reaches 20 and remains constant afterwards. The reason behind this fast pace of convergence is due to the wisely-assumed learning parameters for the adaptive controller.

5.7. Summary

In this chapter, a self-organising adaptive fuzzy logic controller for non-affine nonlinear systems has been discussed. The tracking error is shown to be uniformly ultimately bounded.

All the adaptive parameters and the tracking error are shown to be bounded. The stability checks consist of two stages. First, the implicit function theorem is used to show the existence of the ideal control. Afterwards, for the Lyapunov stability check an extension form of universal approximation theory is discussed. In contrast, the other control algorithms proposed in the introduction of this chapter, this method does not have any restrictions. The controller proposed in the non-affine nonlinear system is also applicable for much simpler state space equations in the affine case. In the end, two examples are presented to discuss this method in practice.

CHAPTER 6

SEMI-ACTIVECONTROLLED BUILDINGS UNDER EXCITATIONS

6.1. Introduction

When seismic vibration suppression devices are installed in building structures, these structures are considered to be smart structures. The optimised placement of sensors, actuators and vibration suppression devices is very efficient in reducing the vibration induced in structures when subjected to external excitations (Adeli 2008). Research has been conducted for decades on vibration suppression of structures due to external excitations or dynamic loading such as wind or heavy traffic (Nishitani & Inoue 2001). Semi-active vibration devices take into account both the features of passive and damping vibration suppression devices (Symans & Constantinou 1999).The typical semi-active vibration control devices include fluid viscous dampers and magneto rheological (MR) dampers. The MR damper requires lower voltage which is easily supplied by batteries, therefore making it very popular (Carlson, Catanzarite & St. Clair 1996). When using MR dampers, a control algorithm needs to be defined which can incorporate its nonlinear characteristics, as well as the nonlinear non-affine state space equations encountered when dealing with the equation of motion of the building structure. In this chapter, a more efficient type of fuzzy logic controller is defined known as self-organising adaptive fuzzy logic control. This intelligent control proposed here is very efficient in dealing with the aforementioned non-affine nonlinear state space equations.

Simulation on a one-storey and five-storey structure has been conducted. Both structures are equipped with a pair of MR dampers. Fuzzy logic controllers and self-organising adaptive fuzzy logic controllers have individually been used and their efficiency in reducing the earthquake-induced vibrations has been compared.

6.2. Structural System

A n-degree-of-freedom building structure is considered. The external excitations can be wind or earthquake. The equation of motion is presented below:

$$M\ddot{x} + C\dot{x} + Kx = \Gamma f + M\Lambda\ddot{x}_g; \tag{6.1}$$

where m is the mass of the structure, c is the damping of the structure, k is the stiffness of the structure, $x(t)$ is the displacement matrix, $\dot{x}(t)$ is the velocity matrix, $\ddot{x}(t)$ is the acceleration matrix of the building structure;

$x(t) = [x_1, x_2, \dots, x_n]^T$, $\dot{x}(t) = [\dot{x}_1, \dot{x}_2, \dots, \dot{x}_n]^T$, $\ddot{x}(t) = [\ddot{x}_1, \ddot{x}_2, \dots, \ddot{x}_n]^T$
$f = [f_1, f_2, \dots, f_n]^T, \Lambda = [1,1, \dots ,1]^T$.

Matrix Γ is the gain matrix determining the control effect on the building, Λ is a distribution matrix, f is the control force provided by the controller and $\ddot{x}_g(t)$ is the ground acceleration of the earthquake.

The mass matrix is considered as below:

$$M = diag([m_1, \dots, m_n]). \tag{6.2}$$

The stiffness matrix is as below:

$$K = \begin{bmatrix} k_1 + k_2 & -k_2 & 0 & 0 \\ -k_2 & \cdots & \cdots & 0 \\ 0 & \cdots & \cdots & -k_n \\ 0 & 0 & -k_n & k_n \end{bmatrix}. \tag{6.3}$$

The damping matrix is as below:

$$C = \begin{bmatrix} c_1 + c_2 & -c_2 & 0 & 0 \\ -c_2 & \cdots & \cdots & 0 \\ 0 & \cdots & \cdots & -c_n \\ 0 & 0 & -c_n & c_n \end{bmatrix}. \tag{6.4}$$

The equation of motion is transformed into state space equations in which a system state is defined $y = [x^T \quad \dot{x}^T]^T \in R^{2n}$ and has the below form:

$$\dot{y} = Ay + Bf + E; \tag{6.5}$$

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \qquad B = \begin{bmatrix} 0 \\ M^{-1}\Gamma \end{bmatrix}, \qquad E = \begin{bmatrix} 0 \\ \Lambda \end{bmatrix} \ddot{x}_g \ ; \tag{6.6}$$

where A is the system matrix, B is the gain matrix and E is the external excitation matrix.

6.3. Structure equipped with MR dampers

An n-storey structure is subjected to external excitations, in this case earthquakes, in which MR dampers are installed in the structure and the control forces, are provided by the controller. The equation of motion of this structure takes the form presented in equation (6.1) in which the control input is the control force which is known as an 'indirect' control algorithm.

For the direct control algorithm, the current is the control input which is supplied to the MR damper. This damper is modelled by the static hysteresis model, as discussed in chapter 2.

The schematic diagram of an n-storey structure equipped with a pair of MR dampers in each floor and subjected to seismic excitation is shown in figure 6.1.

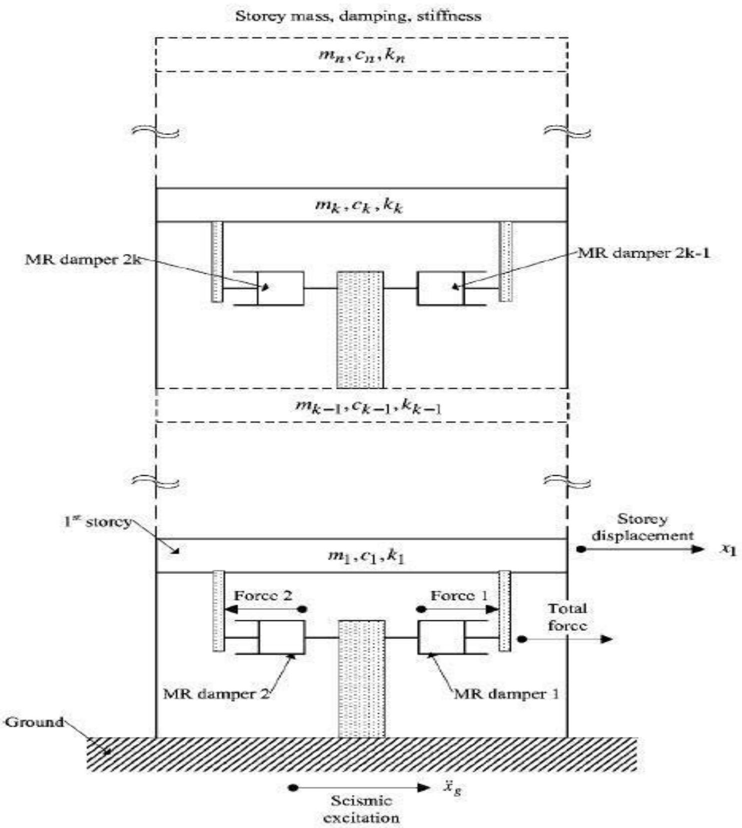


Figure 6.1. System schematic diagram

6.4. Damper modeling and setup

A set up of two MR dampers installed in one storey is shown in the figure below:

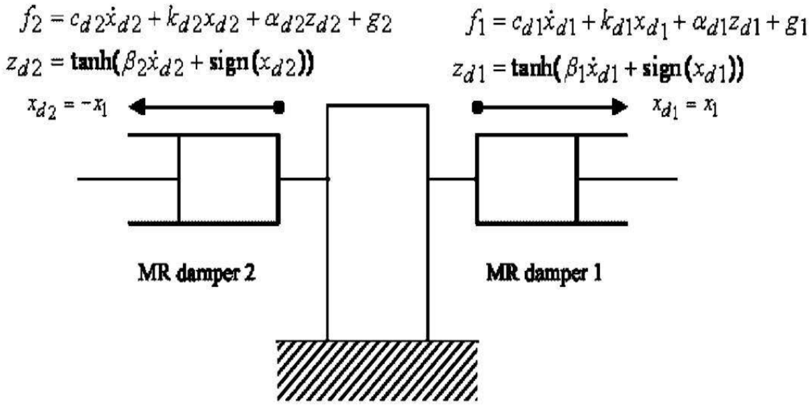


Figure 6.2. Damper differential configurations

The static hysteresis model, introduced in chapter 2, is used for the direct control in which the control input is the current supplied to the MR damper. The damper forces generated are presented below:

$$f_j = c_{dj}\dot{x}_{dj} + k_{dj}x_{dj} + \alpha_{dj}z_{dj} + g_j$$
$$z_{dj} = \tanh(\beta_j\dot{x}_{dj} + \delta_j sign(x_{dj})); \tag{6.7}$$

where $j = 1,2$ are for the left and right damper in the figure above and the damper parameters $c_{dj}, k_{dj}, \alpha_{dj}, g_j, \beta_j, \delta_j$; $j = 1,2$ depend on the current supplied to the MR damper. The damper parameters and current is a polynomial of order one or two (Kwok et al. 2006).

Based on the setup in the figure above, the displacements of the two dampers are opposite in sign, in which:

$$x_1 = x_{d1} = -x_{d2}\,, \dot{x}_1 = \dot{x}_{d1} = -\dot{x}_{d2}. \tag{6.8}$$

Therefore, the coefficients which are dependent on the current (Kwok et al. 2006) have the below form:

$$c_{d1} = c_{d11} + c_{d12}i_{d1}, k_{d1} = k_{d11} + k_{d12}i_{d1}; \tag{6.9}$$

where i_{d1} is the current provided to the damper on the right. The forces of the damper are presented below:

$$f_1 = c_{d11}\dot{x}_1 + c_{d12}\dot{x}_1 i_{d1} + k_{d11}x_1 + k_{d12}x_1 i_{d1} + \alpha_{d1}z_{d1} + g_1 \tag{6.10}$$
$$f_2 = -c_{d21}\dot{x}_1 - c_{d22}\dot{x}_1 i_{d2} - k_{d21}x_1 - k_{d22}x_1 i_{d2} + \alpha_{d2}z_{d2} + g_2. \tag{4.11}$$

The effective damping force is the difference of the two MR damper forces, $f = f_1 - f_2$, as presented in the equations below:

$$f = (c_{d11} + c_{d21})\dot{x}_1 + (k_{d11} + k_{d21})x_1 + (c_{d12}\dot{x}_1 + k_{d12}x_1)i_{d1}$$
$$+(c_{d22}\dot{x}_1 + k_{d22}x_1)i_{d2} + \alpha_{d1}z_{d1} - \alpha_{d2}z_{d2} + g_1 - g_2\ . \qquad (6.12)$$

Assuming equal currents supplied to the dampers, therefore $i_{d1} = i_{d2} = i$, then

$$f = (c_{d11} + c_{d21})\dot{x}_1 + (k_{d11} + k_{d21})x_1 + \big((c_{d12} + c_{d22})\dot{x}_1 + (k_{d12} + k_{d22})x_1\big)i$$
$$+\alpha_{d1}z_{d1} - \alpha_{d2}z_{d2} + g_1 - g_2. \qquad (6.13)$$

Assuming the offset forces $g_j = g_{j1} + g_{j2}i$, $(j = 1{,}2)$. For similar dampers; $g_1 = g_2$, and therefore, the offset forces cancel each other. Therefore, the total force in equation (6.13) takes the form below:

$$f = (c_{d11} + c_{d21})\dot{x}_1 + (k_{d11} + k_{d21})x_1 + \big((c_{d12} + c_{d22})\dot{x}_1 + (k_{d12} + k_{d22})x_1\big)i$$
$$+\alpha_{d1}z_{d1} - \alpha_{d2}z_{d2}. \qquad (6.14)$$

Assuming the hysteretic parameters as below:

$$z_{d1} = \tanh\big(\beta_1\dot{x}_{d1} + (\delta_{11} + \delta_{12}i)sign(x_{d1})\big) \qquad (6.15)$$
$$z_{d2} = \tanh(\beta_2\dot{x}_{d2} + (\delta_{21} + \delta_{22}i)sign(x_{d2})). \qquad (6.16)$$

Assuming the dampers are identical and the currents supplied to these dampers are equal, the hysteresis variable takes the below form:

$$z_{d1} = \tanh\big(\beta_1\dot{x}_1 + (\delta_{11} + \delta_{12}i)sign(x_1)\big) = \tanh(\psi) \qquad (6.17)$$
$$z_{d2} = \tanh\big(-\beta_1\dot{x}_1 + (\delta_{11} + \delta_{12}i)sign(x_1)\big) = \tanh(-\psi); \qquad (6.18)$$

where $\tanh(\psi) = -\tanh(-\psi)$.Therefore $z_{d1} = -z_{d2} = z_d$. The total force eventually takes the form below:

$$f = c_{d1}\dot{x}_1 + k_{d1}x_1 + (c_{d2}\dot{x}_1 + k_{d2}x_1)i + \alpha z_d; \qquad (6.19)$$

where $c_{d1} = c_{d11} + c_{d21}$, $c_{d2} = c_{dj1} + c_{dj2}$, $k_{dj} = k_{dj1} + k_{dj2}$, $j = 1{,}2$
and $\bar{\alpha} = \alpha_{d1} + \alpha_{d2}$.

Based on the assumptions above, the offset forces are cancelled in contrast to the stiffness and damping of the damper forces which are added up in the overall force for the MR damper, which is dependent on the current supplied. If this cancellation was not possible, the equation (6.19) would have extra parameters, for example, αz_d, and therefore a robust controller would be required.

6.5. Structures with embedded MR dampers

The equation of motion for an arbitrary floor k^{th} when a pair of MR dampers are installed in it, takes the form below:

$$m_k\ddot{x}_k + c_k\dot{x}_k + k_kx_k = -(c_{d1k}\dot{x}_k + k_{d1k}x_k + (c_{d2k}\dot{x}_k + k_{d2k}x_k)i_k + \alpha_k z_{dk}) + m_k\ddot{x}_g; \tag{6.20}$$

where m_k, c_k and k_k are the mass, damping and stiffness.

Assuming pairs of dampers are embedded on the 1^{st},..,k^{th},.. and n^{th}floors with the current vector $i = [i_1 \dots i_k \dots i_n]^T$, the state space equation takes the form below:

$$\dot{y} = Ay + B(y)i + E; \tag{6.21}$$

where

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix},$$

$$B = \begin{bmatrix} 0_n & 0_n & 0_n \\ -{m_1}^{-1}(c_{1_1}\dot{x}_1 + k_{1_1}x_1) & 0 & 0 \\ \vdots & \vdots & \vdots \\ 0 & -{m_k}^{-1}(c_{1_k}\dot{x}_k + k_{1_k}x_k) & 0 \\ \vdots & \vdots & \vdots \\ 0 & 0 & -{m_n}^{-1}(c_{1_n}\dot{x}_n + k_{1_n}x_n) \end{bmatrix} \tag{6.22}$$

$$E = E_1 + E_2, E_1 = \begin{bmatrix} 0_n \\ -{m_1}^{-1}\alpha_1 z_1 \\ \vdots \\ -{m_k}^{-1}\alpha_k z_k \\ \vdots \\ -{m_n}^{-1}\alpha_n z_n \end{bmatrix}, E_2 = \begin{bmatrix} 0 \\ \Lambda \end{bmatrix}\ddot{x}_g \ ;$$

where all the elements of matrix K and C are the same as K and C in equation (6.2), except the k^{th} floor, where the MR dampers are installed and $K_k = K_k + k_{0_k}$, and $C_k = C_k + c_{1_k}$ (k=1,2,..,n). Matrix E results from the inaccuracy in modelling or not identical MR dampers installed in one floor.

6.6. Fuzzy logic controller

Fuzzy logic is a model-free approach as it does not require elaborate mathematical functions to tackle in its design. Fuzzy logic systems are efficient when solving rigorous control problems. The best features of fuzzy logic systems are that they can be nonlinear, adaptive, and handle uncertainty in the system.

The fuzzy logic controller uses data from the sensors and converts them into linguistic or fuzzy membership functions by the *fuzzification* process.

This chapter focuses on the structural model of an n^{th} storey structure. The structure discussed has a pair of MR dampers embedded in it and fuzzy logic controllers as the control devices. The equation of motion of the structure with the nonlinear characteristics of the MR damper has been considered and discussed. In the following sections, two case studies; a one storey and a five storey structure are being discussed.

6.7. Simulations of a one storey structure embedded with MR dampers and different controllers

The building under consideration is a benchmark one storey model with one pair of identical MR dampers defined by Ha (2008) for studies on response control of earthquake-excited buildings. An earthquake is subjected to this structure and the vibrations due to this external excitation are shown to be reduced dramatically via the dampers installed and the fuzzy logic controller versus the self-organising adaptive fuzzy logic controller.

6.7.1. Structural model of a one storey building

The numerical modeling of a one storey steel structure is presented here. The external excitation is an earthquake, El Centro, in this case. The fundamental frequency of this earthquake is *1.5 Hz* whilst the fundamental frequency of the structure is *4 Hz*; therefore the destructive effect of resonance is prevented. The *1^st^* vibration mode (fundamental frequency of the structure) is considered. A pair of magnetorheological (MR) dampers are used here as semi-active vibration control devices. A static hysteresis model is used to model the damper formula and incorporate it in the equation of motion of the structure. The current-controlled problem of the smart structure system is formulated in non-affine nonlinear state space equations due to the nonlinear characteristics of this damper. The objective is to mitigate the vibration of the structure therefore the desired output is the displacements that are converging to zero. Self-organising adaptive fuzzy logic systems are used to overcome the non-affine nonlinear state space equations encountered when solving the equation of motion of the structure.

6.7.2. Simplified evaluation model

Numerical simulations were conducted in MATLAB and SIMULINK to test the efficiency of the control algorithms developed. This can be seen from the block diagram of the system:

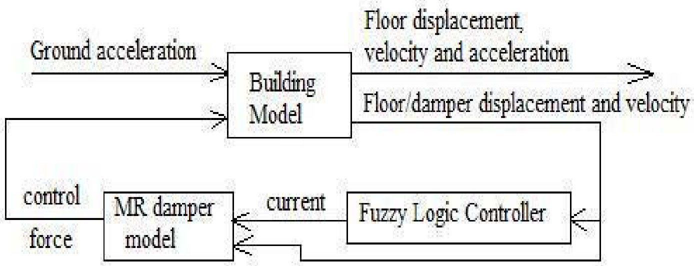


Figure 6.3. System block diagram

The equation of motion of the building equipped with a pair of MR dampers installed in the first storey and a fuzzy logic controller can be presented as:

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 = -[c_{d1}\dot{x}_1 + k_{d1}x_1 + (c_{d2}\dot{x}_1 + k_{d2}x_1)i + \alpha z_d] + m_1\ddot{x}_g \,; \tag{6.23}$$

where

$$\alpha = \alpha_{d1} + \alpha_{d2} = \alpha_0 + \alpha_1 i + \alpha_2 i^2$$
$$z_d = \tanh(\beta_1\dot{x}_1 + \delta_1 sign(x_1))$$
$$\delta_1 = \delta_{10} + \delta_{11} i \,;$$

where $\ddot{x}_1$ is the acceleration vector, $\dot{x}_1$ is the velocity vector, x_1 is the displacement vector of the first floor. m_1 is the mass, c_1 is the damping, k_1 is the stiffness of the first storey. i is the current produced by the fuzzy logic controller and provided to the MR damper.

The equation of motion of the structure, in equation (6.23), can be transformed into state space equations as shown below:

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = \left(\frac{-c_1}{m_1}\right)\dot{x}_1 + \left(\frac{-k_1}{m_1}\right)x_1 - \left(\frac{c_{d1} + c_{d2}\ i}{m_1}\right)\dot{x}_1 - \left(\frac{k_{d1} + k_{d2}\ i}{m_1}\right)x_1 - \left(\frac{\alpha}{m_1}\right)tanh(z) + \ddot{x}_g$$
$$y = x_1;$$

where

$$\alpha = \alpha_0 + \alpha_1 i + \alpha_2 i^2 \ , \ z \ = \beta \dot{x}_1 + (\delta_{10} + \delta_{11} i) sign x_1. \tag{6.24}$$

In the simulation:

$$m_1 = 1000 \ N, k_1 = 576000 \ N/m \ , c_1 = 100000 \ Ns/m \ .$$

The characteristics of the MR damper are:

$\alpha_2 = -488 \ ; \alpha_1 = 1836 \ ; \alpha_0 = 64 \ ; \beta = 100 \ ;$

$\delta_{10} = 0.58 \ ; \delta_{11} = 0.3 \ ;$

$k_{d1} = 10200 \ ; k_{d2} = -3400 \ ;$

$c_{d1} = 2464 \ ; \ c_{d2} = 3858 \ .$

The external excitation subjected to the structure is the El Centro earthquake (M_w=7.1), normalized to 2g as the peak ground acceleration (PGA), as shown in figure 6.4. This earthquake is provided by the strong motion data base in University of Berkeley at California (Pacific Earthquake Engineering Research Centre).

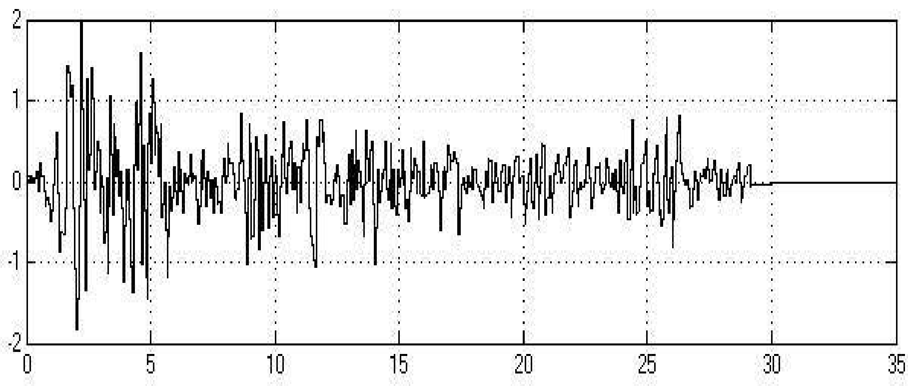


Figure 6.4. El Centro earthquake acceleration time history

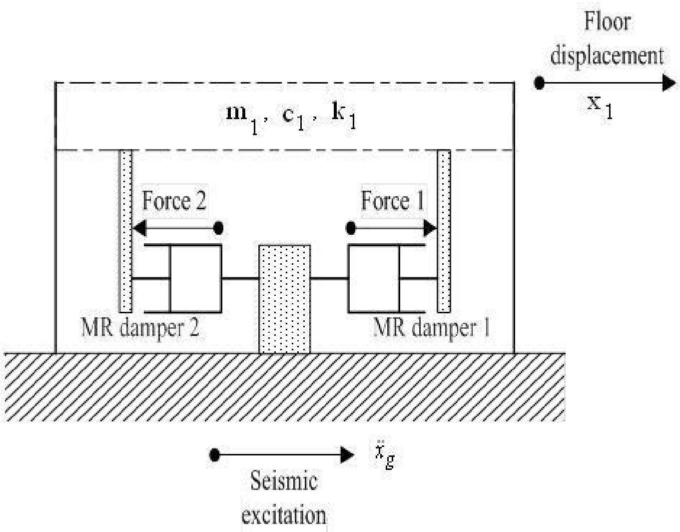


Figure 6.5. Schematic of a one storey structure equipped with MR dampers

6.7.3. Designing the fuzzy logic controller

The fuzzy logic controller is designed using three inputs, all having two triangular membership functions, and one output having eight constant membership functions. The inputs are the displacement (x_1) and velocity (x_2) of the first storey and the variations of current with respect to time $(\frac{d}{dt}i)$. The output is the current (i) provided to the MR damper. The fuzzy variables are defined in table 6-1.

Table 6-1- Fuzzy Variables

XN	Negative Displacement
XP	Positive Displacement
VN	Negative Velocity
VP	Positive Velocity
N(Idot)	Negative Variations in Current
P(Idot)	Positive Variations in Current

The membership functions for the input variables are shown below:

- For the first input which is the displacement:

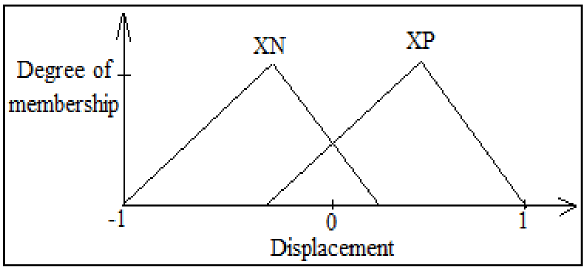


Figure 6.6. The first input of the fuzzy logic controller

- For the second input which is the velocity:

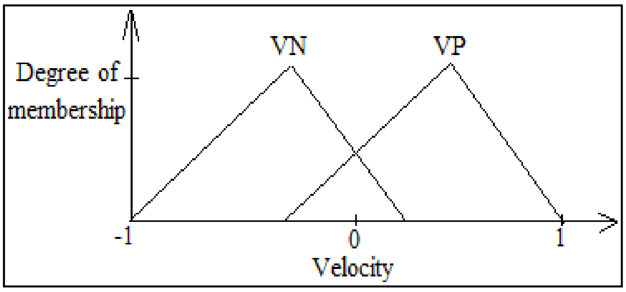


Figure 6.7. The second input of the fuzzy logic controller

- For the third input which is the variations of current:

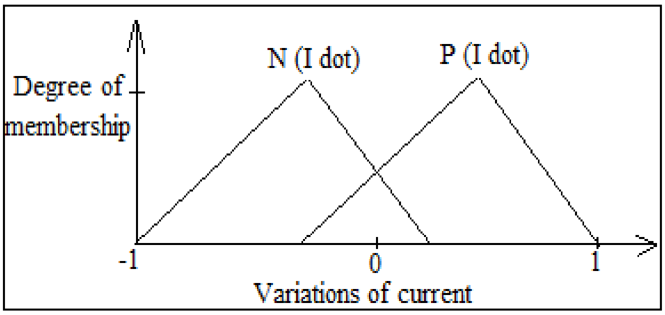


Figure 6.8. The third input of the fuzzy logic controller

The membership functions for the output variable are constant:

$mf_1 = 0.5$

$mf_2 = 0$

$mf_3 = 0.1667$

$mf_4 = 0.3333$

$mf_5 = 0.5$

$mf_6 = 0.6667$

$mf_7 = 0.8333$

$mf_8 = 1$.

The fuzzy logic controller rules are as below:

1. If x_1 is *XN* and x_2 is *VN* and $\frac{d}{dt}i$ is *N(Idot)*, Then i is mf_1.
2. If x_1 is *XN* and x_2 is *VN* and $\frac{d}{dt}i$ is *V(Idot)* , Then i is mf_2.
3. If x_1 is *XN* and x_2 is *VP* and $\frac{d}{dt}i$ is *N(Idot)* , Then i is mf_3.
4. If x_1 is *XN* and x_2 is *VP* and $\frac{d}{dt}i$ is *V(Idot)*, Then i is mf_4.
5. If x_1 is *XP* and x_2 is *VN* and $\frac{d}{dt}i$ is *N(Idot)*, Then i is mf_5.
6. If x_1 is *XP* and x_2 is *VN* and $\frac{d}{dt}i$ is *V(Idot)* , Then i is mf_6.
7. If x_1 is *XP* and x_2 is *VP* and $\frac{d}{dt}i$ is *N(Idot)* , Then i is mf_7.
8. If x_1 is *XP* and x_2 is *VP* and $\frac{d}{dt}i$ is *V(Idot)* , Then i is mf_8.

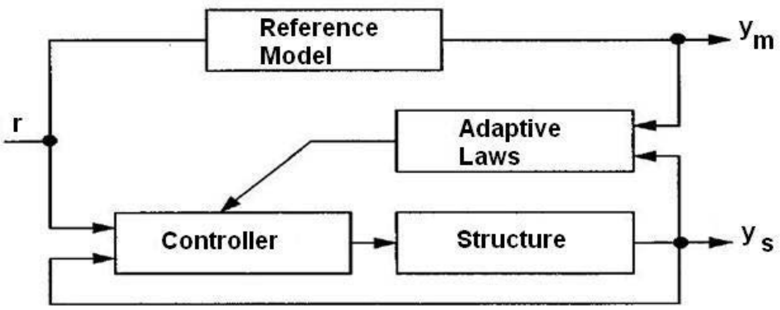


Figure 6.9. Adaptive fuzzy logic controller

The control objective is to make the displacement of the first storey ($y = x_1$) track the reference signal which is defined as zero matrices. The flowchart algorithm of adaptive fuzzy logic controllers is shown in figure 6.9.

The operating variable ranges are chosen as follows:

$$x_1 \epsilon [-0.003, 0.003] \, ; \; x_2 \epsilon [-0.04, 0.04]; \; i \epsilon [0,2] \, .$$

The parameters of the controller are chosen as follows:

$$k = [1 \;\; 1]^T; Q = \begin{bmatrix} 20 & 0 \\ 0 & 10 \end{bmatrix}; P = \begin{bmatrix} 25 & 10 \\ 10 & 15 \end{bmatrix}; \; \gamma = 100 \, .$$

6.7.4. Designing the self-organising adaptive fuzzy logic controller

As mentioned in the previous chapter, fixed-structured adaptive fuzzy logic control requires designers to choose the rule base and membership functions by trial and error. This task is not trivial as long as exact mathematical models of plants are not known. Quite often, the structure used is either unnecessarily large or too small to adequately represent a plant. From this perspective, self-organising adaptive fuzzy logic control is more advantageous as it can automatically add and remove rules from a fuzzy system.

A variable called *self-organising flag* is used to indicate when the self-organising performs. When the self-organising flag switches from *1* to *-1* or *-1* to *1*, it indicates a change in the fuzzy system structure has occurred.

Table 6-2- Different set ups

	mf threshold	Error Threshold	a_0	center distance threshold	B_{rules}
Set up 1	0.5	0.5	[1 1 1]	[0.5 0.5 0.5]	100
Set up 2	0.5	2	[2 2 2]	[0.5 0.5 0.5]	15
Set up 3	0.5	0.5	[1 1 1]	[0.5 0.5 0.5]	20
Set up 4	0.5	0.5	[0.5 0.5 0.5]	[0.25 0.25 0.25]	20
Set up 5	0.5	0.5	[0.5 0.5 0.5]	[0.25 0.25 0.25]	20
Set up 6	0.5	0.5	[0.25 0.25 0.25]	[0.125 0.125 0.125]	20
Set up 7	0.5	2	[0.5 0.5 0.5]	[0.25 0.25 0.25]	15
Set up 8	0.5	2	[0.5 0.5 0.5]	[0.125 0.125 0.125]	20
Set up 9	0.5	0.25	[0.5 0.5 0.5]	[0.25 0.25 0.25]	20

Different setups for the structure-learning parameters are performed, as shown in table 6-2; setup 2 has shown the best results. a_0 is half of the maximum predefined spreads of the triangular membership functions in each dimension.

The SIMULINK block in MATLAB, used for self-organising adaptive fuzzy logic controller for non-affine nonlinear systems is shown in figure 6.10.

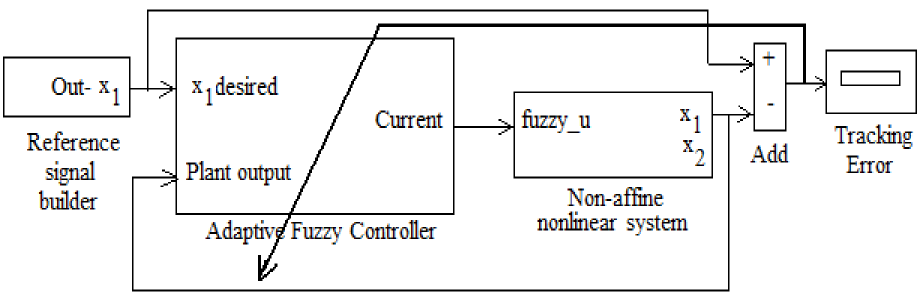


Figure 6.10. Self-organising adaptive fuzzy logic controller

In this SIMULINK block, a reference signal is defined. As mentioned in the previous sections, this signal is a zero matrix, defined for the desired displacement of this one storey building structure since the main objective of these vibration control devices is to suppress the displacement resulting from the external excitations. The block for the adaptive fuzzy logic controller is shown in figure 6.14, in which the desired reference and the plant output are the inputs to this block. The output of this block is the current. The input is defined based on a series of trial and error presented in table 6-2, in which the best structure-learning parameters are chosen for the adaptive control. The SIMULINK block for the non-affine nonlinear system is shown in figure 6.15, in which the non-affinity in the state space equations is modeled into a series of blocks where the exact mathematical calculations seen in the state space equations are presented. The external excitation is a scaled earthquake subjected to the structure. The structural characteristics (mass, damping and stiffness), the MR damper equations and the fuzzy logic controller are modeled in the non-affine nonlinear system block. The input to this block is the current provided from the adaptive fuzzy logic controller block which is given to the MR damper. The output is the displacement and velocity of the first storey of the structure. The loop in figure 6.10 continues until the tracking error converges to zero. The tracking error is the difference between the displacement output and the desired displacement output. It is an indicator of the convergence of the system, or in other words, the termination of the iteration procedure. Then, the fuzzy logic controller is known to be adapted. Therefore, there is an initial set of membership functions assumed for the inputs and the outputs and a final set of membership functions after the adaptation of the fuzzy logic controller, presented in figures 6.18 to 6.21.

6.7.5. Simulation results of the one storey structure

The simulation analysis of the one storey building with MR dampers and fuzzy logic controller is incorporated into the SIMULINK program in MATLAB, using a variable integration time step. The differential equation of motion is solved using the fourth-order *Runge-Kutta*. The external excitation subjected to the structure is the El Centro earthquake $(M_w=7.1)$ normalized to $2g$.

The one storey building structure without either MR dampers or any other controllers (fuzzy logic controllers or self-organising adaptive fuzzy logic controllers) due to El Centro earthquake is shown in figure 6.14.

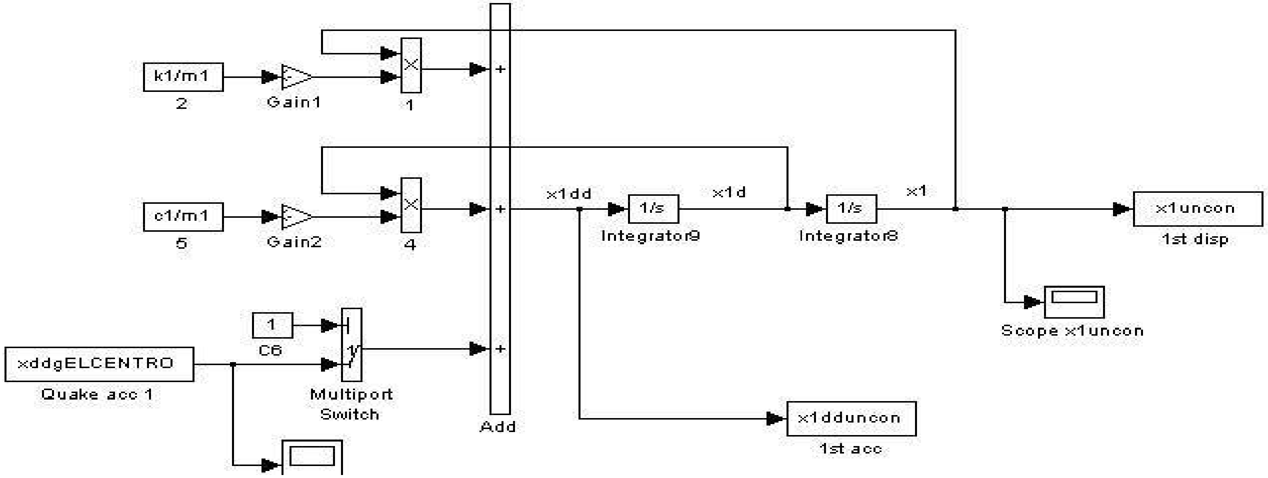


Figure 6.11. Simulink model of a one storey building model without MR dampers and fuzzy logic controllers

The SIMULINK model in MATLAB of the one storey building structure embedded with MR dampers and fuzzy logic controller due to El Centro earthquake excitations is shown in figure 6.12.

The SIMULINK model in MATLAB of the one storey structure embedded with MR dampers and self-organising adaptive fuzzy logic controller due to El Centro earthquake excitations is shown in figure 6.13.

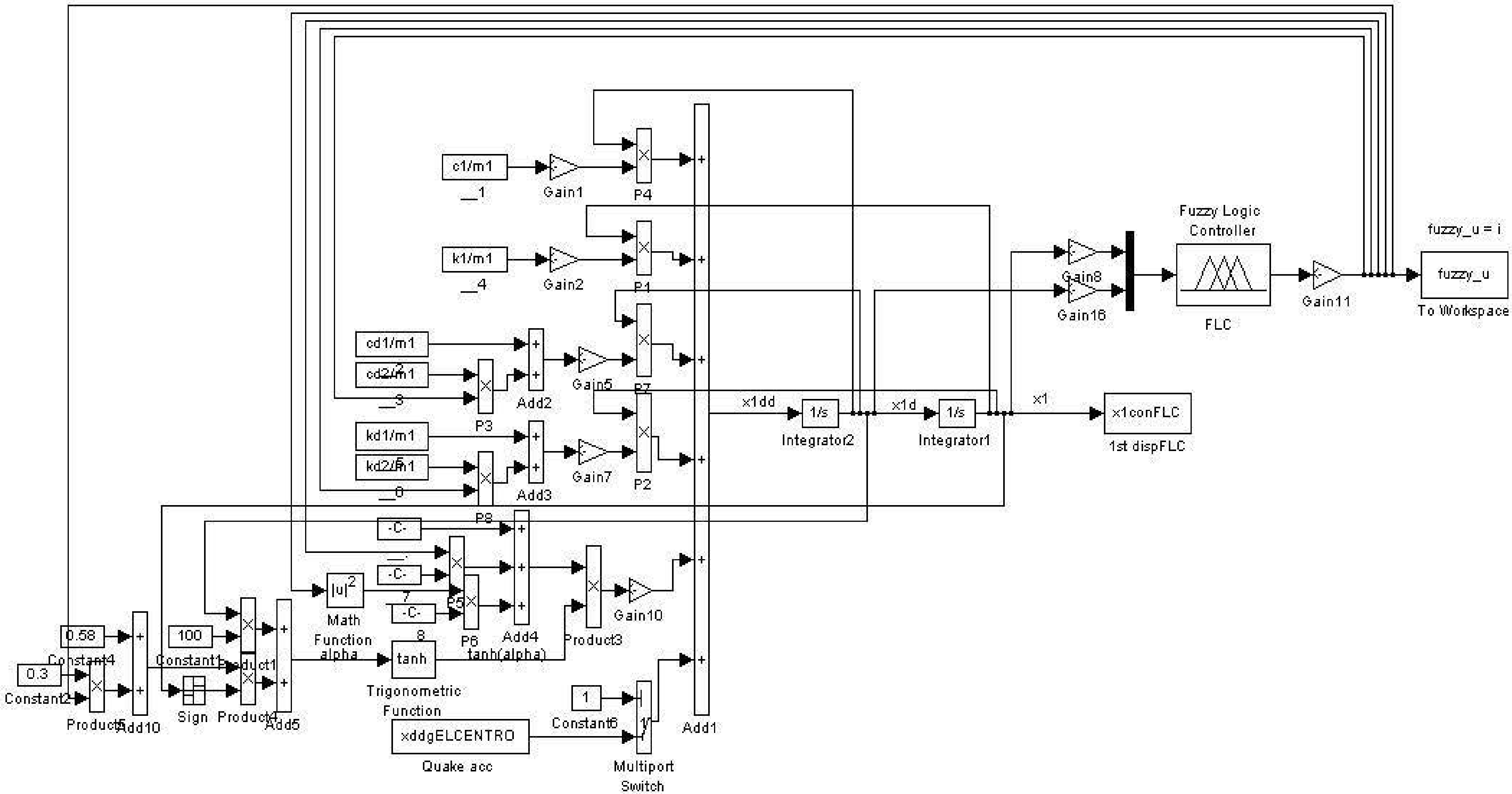


Figure 6.12. Simulink model of a one storey building model with MR dampers and fuzzy logic controller

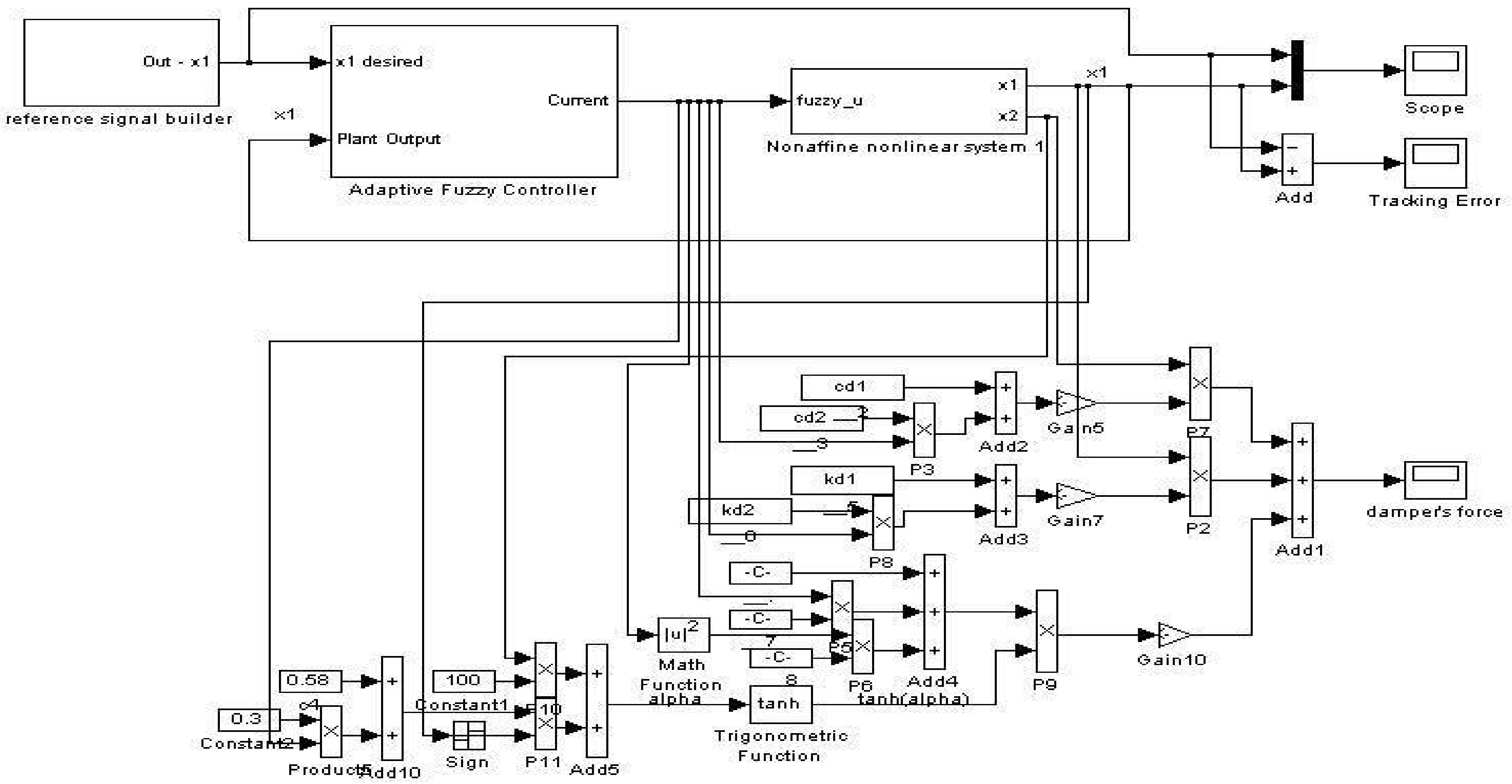


Figure 6.13. Simulink model of a one storey building model with MR dampers and self-organising adaptive fuzzy logic controller

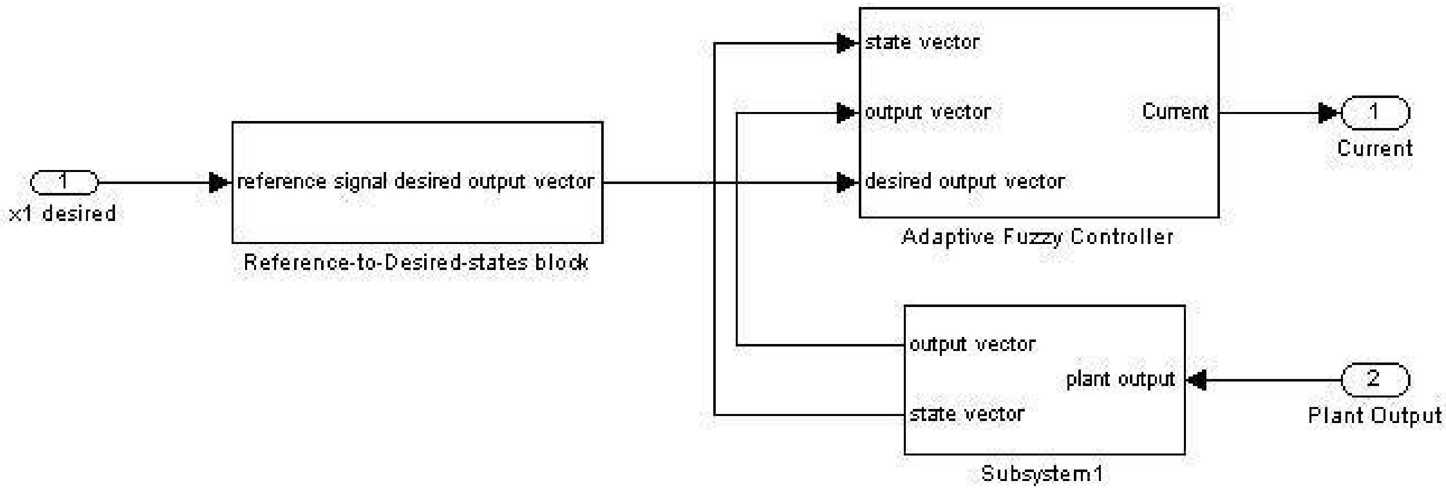


Figure 6.14. Simulink block of the adaptive fuzzy logic controller

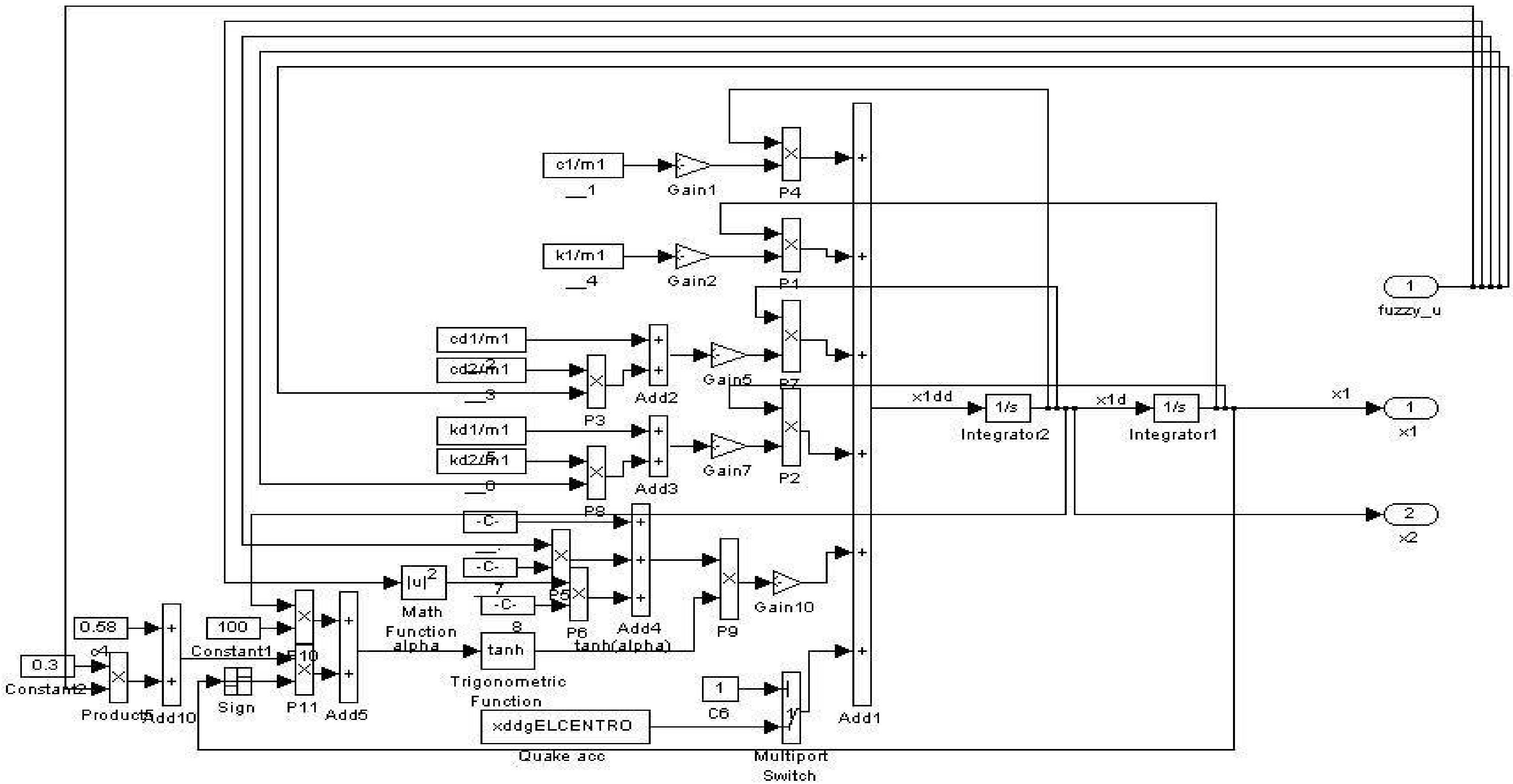


Figure 6.15. Simulink block of non-affine nonlinear system

The SIMULINK block in MATLAB of the adaptive fuzzy logic controller in the self-organising adaptive fuzzy logic controller is shown in figure 6.14. The reference signal is of the same order as the equation of motion of the structure.

The SIMULINK block in MATLAB of the non-affine nonlinear system in the self-organising adaptive fuzzy logic controller is shown in figure 6.15.

The displacement and acceleration time history of this particular one storey building embedded with MR dampers and self-organising adaptive fuzzy logic controller is shown in figure 6.16 and 6.17.

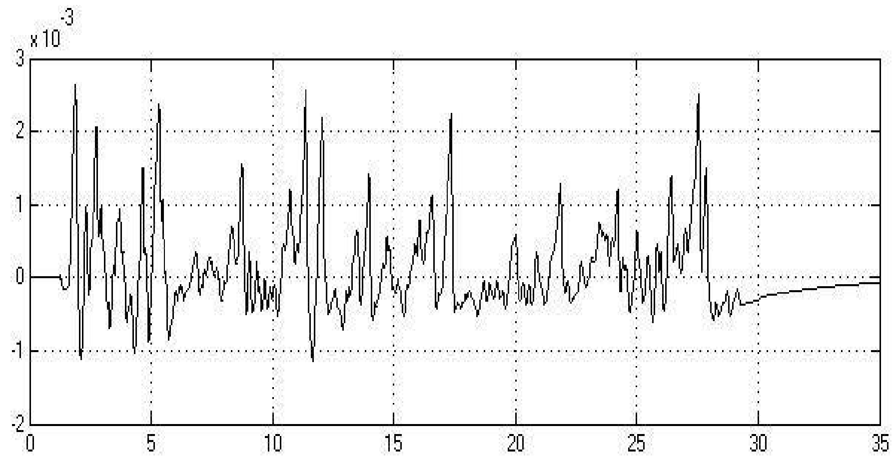


Figure 6.16. Displacement time history (m) of the one storey structure

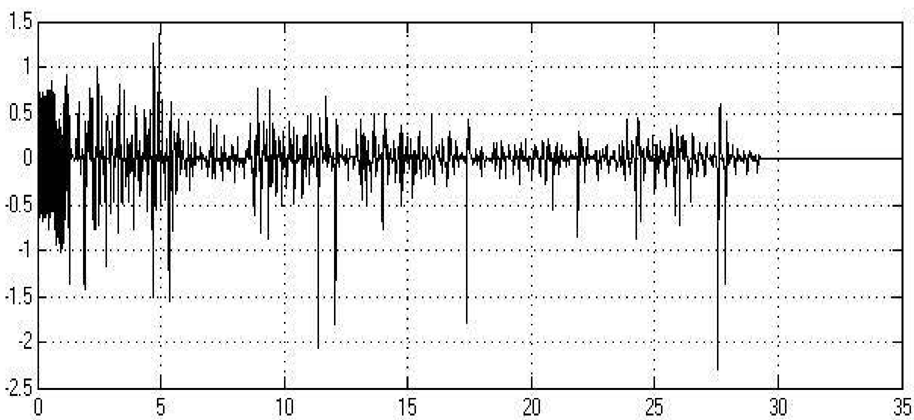


Figure 6.17. Acceleration time history (m/s^2) of the one storey structure

The initial fuzzy logic controller has 8 rules with two membership functions in each input dimension, as shown in figure 6.18.

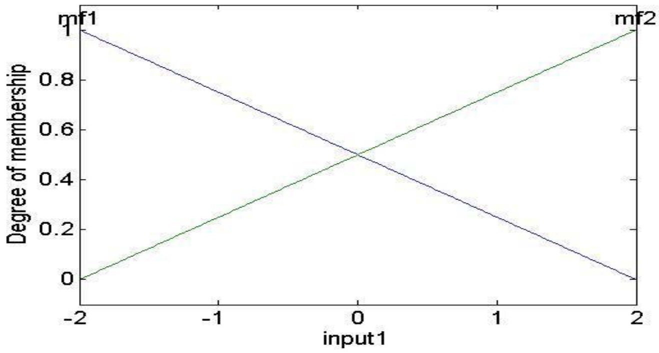


Figure 6.18. Initial membership functions for all three input variables

The simulation results are shown below. A variable called *self*-organising *flag* is used to indicate when the self-organising performs. When the self-organising flag switches from *1* to *-1* or *-1* to *1*, it indicates a change in the fuzzy system structure has occurred.

It can be observed that the controller successfully controls the non-affine nonlinear system to track the reference signal. Self-organising happens in the 2^{nd} second, as shown in figure 6.22. The tracking error is within the range $[-0.003\ 0.003]$ as shown in figure 6.23. The current produced by the controller is shown in figure 6.24.

The damping force produced by the damper is the maximum of 3500 N in the 3^{rd} second, as shown in figure 6.25, which can be provided by a RD-1005-3 MR damper. Configurations of this damper are shown in table 6-3.

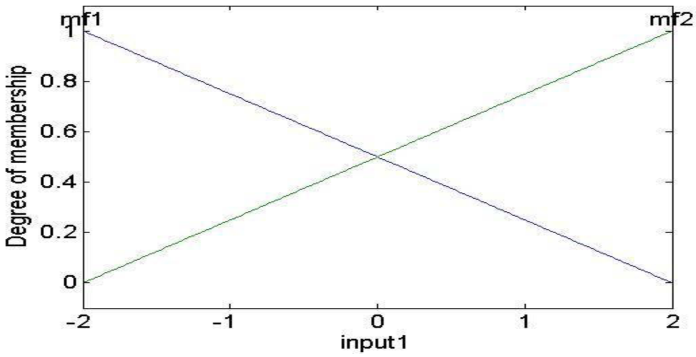


Figure 6.19. Final membership function for input 1

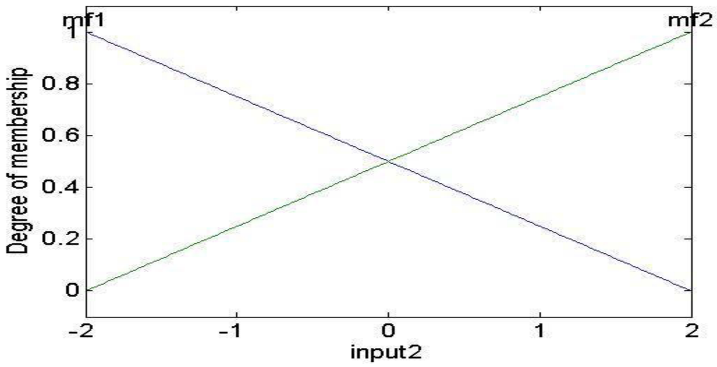


Figure 6.20. Final membership function for input 2

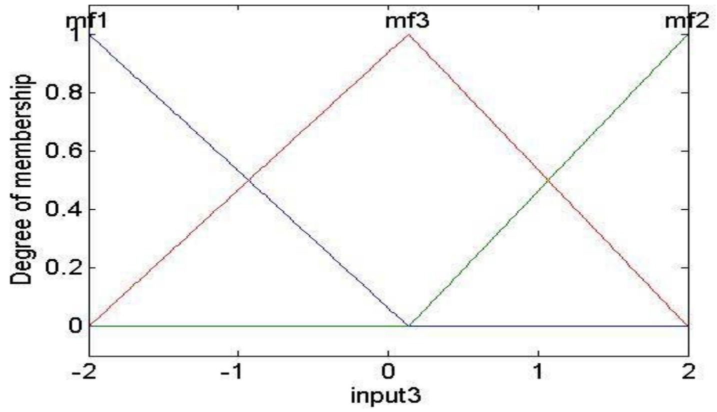


Figure 6.21. Final membership function for input 3

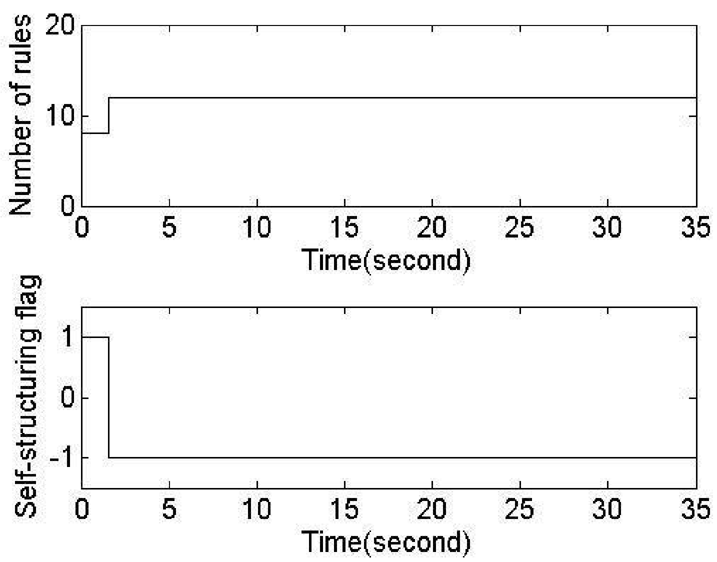


Figure 6.22. Number of rules and Self-organising flag – time

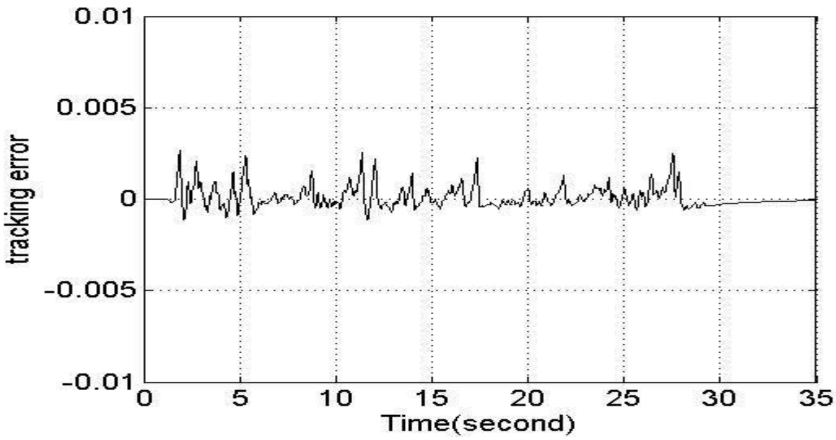


Figure 6.23. Tracking error – time

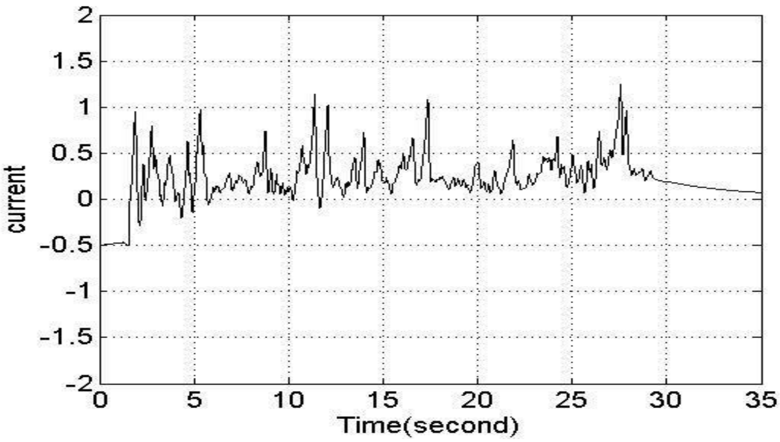


Figure 6.24. Current produced by the Controller (A) – time

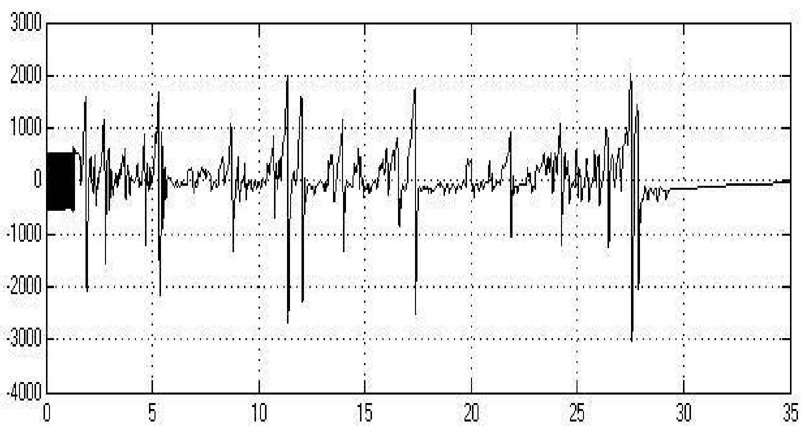


Figure 6.25. Control force provided by the MR damper (N) – time

Table 6-3- Configurations of RD-1005-3 MR damper

Piston-rod movement journey	53mm
Maximal damping force	4 450 N
Maximal input voltage	12 V
Maximal electric current	2 A

6.7.6. Evaluation criteria

The effectiveness on reductions in earthquake-induced vibrations on the structure is further evaluated by a set of performance indices comparing the controlled response against the results obtained from the no-control cases. The criteria, adopted from (Djajakesukma, Samali & Nguyen 2002),(Ohtori et al. 2004) encompass ratios of storey displacements and accelerations. They are formulated as follows:

1. **Absolute storey displacement ratio**

$$J_1 = \frac{\max\{|x_{k,c}(t)|\}}{\max\{|x_{k,u}(t)|\}} \tag{6.25}$$

in which the subscript $k = 1,..,n$ stands for the n-storey indices and subscripts c and u stand for controlled and uncontrolled displacement.

2. **Absolute storey acceleration ratio**

$$J_2 = \frac{\max\{|\ddot{x}_{k,c}(t)|\}}{\max\{|\ddot{x}_{k,u}(t)|\}} \tag{6.26}$$

in which the notation $\ddot{x}$ represents the storey acceleration.

3. **Inter-storey drift ratio**

$$J_3 = \frac{\max\{|\bar{x}_{k,c}(t)|\}}{\max\{|\bar{x}_{k,u}(t)|\}} \tag{6.27}$$

in which the inter-storey displacement is given by $\bar{x}_1 = x_1$, $\bar{x}_{k>1}(t) = x_k(t) - x_{k-1}(t)$

4. **Root mean-squared storey displacement ratio**

$$J_4 = \frac{\tilde{x}_{k,c}(t)}{\tilde{x}_{k,u}(t)} \tag{6.28}$$

in which the root mean-square (RMS) values are calculated from $\tilde{x}_k = \sqrt{T^{-1}\sum\{\delta_t x^2{}_k(t)\}}$, δ_t is the sampling time and T is the total excitation time.

5. RMS storey acceleration ratio

$$J_5 = \frac{\tilde{\ddot{x}}_{k,c}(t)}{\tilde{\ddot{x}}_{k,u}(t)} \tag{6.29}$$

in which the RMS values are calculated as above.

6. Average applied current

$$J_6 = \bar{\imath} = T^{-1} \sum\{\delta_t i(t)\} \tag{6.30}$$

This is the current considered for when the damper is supplied from a battery.

6.7.7. Response ratios

The evaluation ratio for three different earthquakes; El Centro, Kobe and Northridge, for a one storey structure equipped with a pair of MR dampers in the first floor for two cases; fuzzy logic controller and self-organising adaptive fuzzy logic controller, is shown in table 6-4.

Table 6-4- Response ratios

Different Controller	Fuzzy logic controller	Self-organising adaptive fuzzy logic control
El Centro		
J1	1.86	0.67
J2	1.17	0.99
J3	1.86	0.67
J4	0.54	0. 3
J5	2.19	1.29
J6	1.25	0.29
Kobe		
J1	5.17	0.7
J2	5.01	0.98
J3	5.16	0.7
J4	0.51	0.4
J5	5.21	2.82
J6	1.33	0.35
Northridge		
J1	0.87	0.77
J2	1	0.72
J3	0.87	0.77
J4	0.8	0.55
J5	4.41	2.37
J6	1.68	0.3

It is indicated for El Centro earthquake (M_w = 6.9), that the displacements have had more reduction in the case of self-organising adaptive fuzzy logic controllers for this one storey structure embedded with MR dampers. The accelerations seem to have the same amount of reduction, respectively for both controllers. The current provided to the MR damper is four times less in the case of the self-organising adaptive fuzzy logic controller being used.

For Kobe earthquake (M_w= 7.3), the reduction in displacements and accelerations are much more considerable in the case of self-organising adaptive fuzzy logic controllers in comparison to fuzzy logic controllers for this particular one storey structure embedded with MR dampers. The current provided to the MR damper is four times less in the case of self-organising adaptive fuzzy logic controller compared to the fuzzy logic controller.

For Northridge earthquake (M_w= 6.7), the reduction in displacements and accelerations is not much different in both cases. The current provided to the MR dampers is five times less in the case of self-organising adaptive fuzzy logic controllers compared to the fuzzy logic controller being used.

6.7.8. Summary

Self-organising adaptive fuzzy logic systems are used to overcome thenon-affine nonlinear state space equations encountered when solving the equation of motion of the structure. As can be seen, the numerical simulation for self-organising adaptive fuzzy logic controller when dealing with non-affine nonlinear systems is very promising as the explicit formula of the current is not needed and this method is very generic, in the sense that it can be applied to other systems.

In addition, as mentioned earlier, fixed-structured fuzzy logic control requires designers to choose the rule base and membership functions by trial and error, which is a very time-consuming task. Therefore, self-organising adaptive fuzzy logic controller is more advantageous as it can automatically add and remove rules from a fuzzy system.

6.8. Simulation of a five-storey structure embedded with MR dampers and different controllers

6.8.1. Introduction

The building under consideration is a benchmark five storey model with one pair of identical MR dampers defined by (Samali & Al-Dawod 2003) for studies on response control of earthquake-excited buildings. An earthquake is subjected to this structure and the vibrations due to this external excitation are shown to be reduced dramatically via the dampers installed and the fuzzy logic controller versus the self-organising adaptive fuzzy logic controller.

6.8.2. Structural model of a five Storey Building

The five-storey benchmark model, 3.6 m tall steel frame designed and manufactured at the University of Technology Sydney is used for this study as shown in figure 6.26. The model has a footprint of $1.5m \times 1.0m$. It consists of two bays in one direction and a single bay in the other. The beams making up the bulk of each floor are $75 \times 75 \times 4\ mm$ square hollow steel sections. The model lateral stiffness is provided by six high strength $24 \times 24\ mm$ square steel sections. The model is designed to have the first floor heights of $0.7m$. Taking advantage of the fact that masses are effectively lumped at the first floor levels, simplifies the analyses and hence the frame is represented by a five lumped mass dynamic system, yielding a 5×5diagonal mass matrix for both orthogonal directions. The analysis, however, is a *2D* analysis focusing on the motion of the frame along its longer two bay directions. The total mass of the model is $1636.5\ kg$. The five natural frequencies of the model are 2.95, 9.02, 15.68, 21.26 and 25.23 Hz, respectively, and the corresponding damping ratios are 0.4%, 0.69%, 0.63%, 0.2% and 0.14% of critical damping, respectively (Samali & Al-Dawod 2003). Magneto rheological fluid damper is used here since it has the capability of adjusting its viscosity to absorb the seismic shakes of earthquake or dampen the vibrations. Therefore a pair of magneto rheological (MR) dampers is installed in between the 4^{th} and 5^{th} storey. The MR damper has a maximal current of *2A* applied to the magnetizing coil in the damper housing to directly control the MR particle suspension and hence the liquid viscosity to yield the damping force.

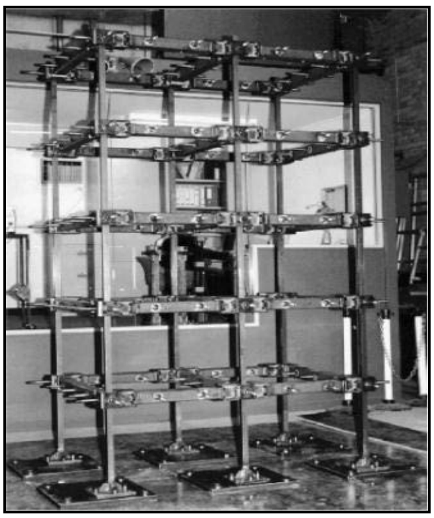


Figure 6.26. Five storey benchmark steel frame

The external excitation subjected to the structure is the El Centro earthquake (M_w=7.1), normalized to *2g* as the peak ground acceleration (PGA), as shown in figure 6.4. This quake is provided by the strong motion data base in University of Berkeley at California (Pacific Earthquake Engineering Research Centre).

6.8.3. Simplified Evaluation Model

The equation of motion of the building equipped with a pair of MR dampers in the k^{th} storey can be presented as:

$$[m_k]\ddot{x}_k + [c_k]\dot{x}_k + [k_k]x_k = -[c_{d1}\dot{x}_k + k_{d1}x_k + (c_{d2}\dot{x}_k + k_{d2}x_k)i + \alpha z_d] + m_k\ddot{x}_g \tag{6.31}$$

Where $\dot{x}_k$ and $\ddot{x}_k$ are respectively the velocity and acceleration of the entire storey, i_k is the current supplied to the pair of dampers (Nguyen 2009).

In this case study, a pair of MR dampers are installed in between the *4^th^* and *5^th^* storey and a fuzzy logic controller is in the last storey. The characteristics of the MR damper are (Ha et al. 2008) :

$$\alpha_2 = -488;\ \alpha_1 = 1836\ ;\ \alpha_0 = 64\,;\beta = 100$$
$$\delta_{10} = 0.58; \delta_{11} = 0.3$$
$$k_{d1} = 10200;\ k_{d2} = -3400$$
$$c_{d1} = 2464;\ \ c_{d2} = 3858\ .$$

6.8.4. Designing the fuzzy logic controller

The fuzzy logic controller has three inputs and one output. The first two inputs are the relative displacement and relative velocity of the 4^{th} and 5^{th} storey (the MR damper is situated in between these storeys) and the third input is the variations of the current with respect to time $(\frac{d}{dt}i)$. The output is the current (i) provided to the MR damper.

Table 6-5- Fuzzy Variables

XN	Negative Displacement
XP	Positive Displacement
VN	Negative Velocity
VP	Positive Velocity
N(Idot)	Negative variations in Current (I dot)
P(Idot)	Positive variations in Current (I dot)

The membership functions of the output variable are constant:

$mf_1 = 0.5$;

$mf_2 = 0$

$mf_3 = 0.1667$

$mf_4 = 0.3333$

$mf_5 = 0.5$

$mf_6 = 0.6667$

$mf_7 = 0.8333$

$mf_8 = 1$.

The rules of the fuzzy logic controller are as below:

1. If x_1 is *XN* and x_2 is *VN* and $\frac{d}{dt}i$ is *N(Idot),* Then i is mf_1.
2. If x_1 is *XN* and x_2 is *VN* and $\frac{d}{dt}i$ is *V(Idot),* Then i is mf_2.
3. If x_1 is *XN* and x_2 is *VP* and $\frac{d}{dt}i$ is *N(Idot),*Then i is mf_3.
4. If x_1 is *XN* and x_2 is *VP* and $\frac{d}{dt}i$ is *V(Idot),* Then i is mf_4.
5. If x_1 is *XP* and x_2 is *VN* and $\frac{d}{dt}i$ is *N(Idot),* Then i is mf_5.
6. If x_1 is *XP* and x_2 is *VN* and $\frac{d}{dt}i$ is *V(Idot),* Then i is mf_6.
7. If x_1 is *XP* and x_2 is *VP* and $\frac{d}{dt}i$ is *N(Idot),* Then i is mf_7.
8. If x_1 is *XP* and x_2 is *VP* and $\frac{d}{dt}i$ is *V(Idot),* Then i is mf_8.

Due to the direct control proposed by Ha et al (2008) and the nonlinear characteristics of MR dampers, non-affine nonlinear state space equations are encountered. Therefore to deal with these equations, non-affine fuzzy logic control (Movassaghi 2012) is proposed.

The control objective is to make the displacement of the 5^{th} storey $(y = x_5)$ track the reference signal which is defined as zero matrices as the displacements are meant to be reduced completely; converging to zero.

The operating variable ranges are chosen as follows:

$$x_1 \epsilon [-0.002, 0.002] \, ; x_2 \epsilon [-0.06, 0.06]; \; i \epsilon [0,2] \, .$$

The parameters of the controller are chosen as follows:

$$k = [1 \;\; 1]^T; Q = \begin{bmatrix} 20 & 0 \\ 0 & 10 \end{bmatrix}; P = \begin{bmatrix} 25 & 10 \\ 10 & 15 \end{bmatrix}; \gamma = 100 \, .$$

6.8.5. Designing the self-organising adaptive fuzzy logic controller

As mentioned in chapter 3, fixed-structured adaptive fuzzy logic control requires designers to choose the rule base and membership functions by trial and error. This task is not trivial as long as exact mathematical models of plants are not known. Quite often, the structure used is either unnecessarily large or too small to adequately represent a plant. From this perspective, self-organising adaptive fuzzy logic control is more advantageous as it can automatically add and remove rules from a fuzzy system.

Table 6-6- Different set ups

	mf threshold	**error threshold**	a_0	**center distance threshold**	B_{rules}
Set up 1	0.5	0.5	[1 1 1]	[0.5 0.5 0.5]	100
Set up 2	0.5	0.5	[0.5 0.5 0.5]	[0.25 0.25 0.25]	20
Set up 3	0.5	2	[1 1 1]	[0.5 0.5 0.5]	15
Set up 4	0.5	0.5	[0.25 0.25 0.25]	[0.125 0.125 0.125]	20

Different set ups for the structure learning parameters are performed, as shown in table 6-6; set up 3 has shown the best results. a_0 is half of the maximum predefined spreads of the triangular membership functions in each dimension.

The SIMULINK block in MATLAB, used for self-organising adaptive fuzzy logic controller for non-affine nonlinear systems is shown in figure 6.27.

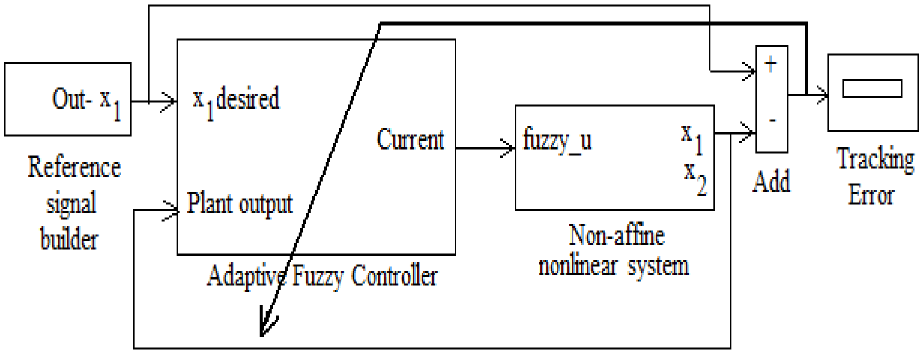


Figure 6.27. Self-organising adaptive fuzzy logic controller for non-affine nonlinear systems

6.8.6. Simulation results of the five storey structure

The five storey structure embedded with MR dampers and self-organising adaptive fuzzy logic controllers due to El Centro earthquake excitations is modeled in SIMULINK in MATLAB, as shown in figure 6.28.

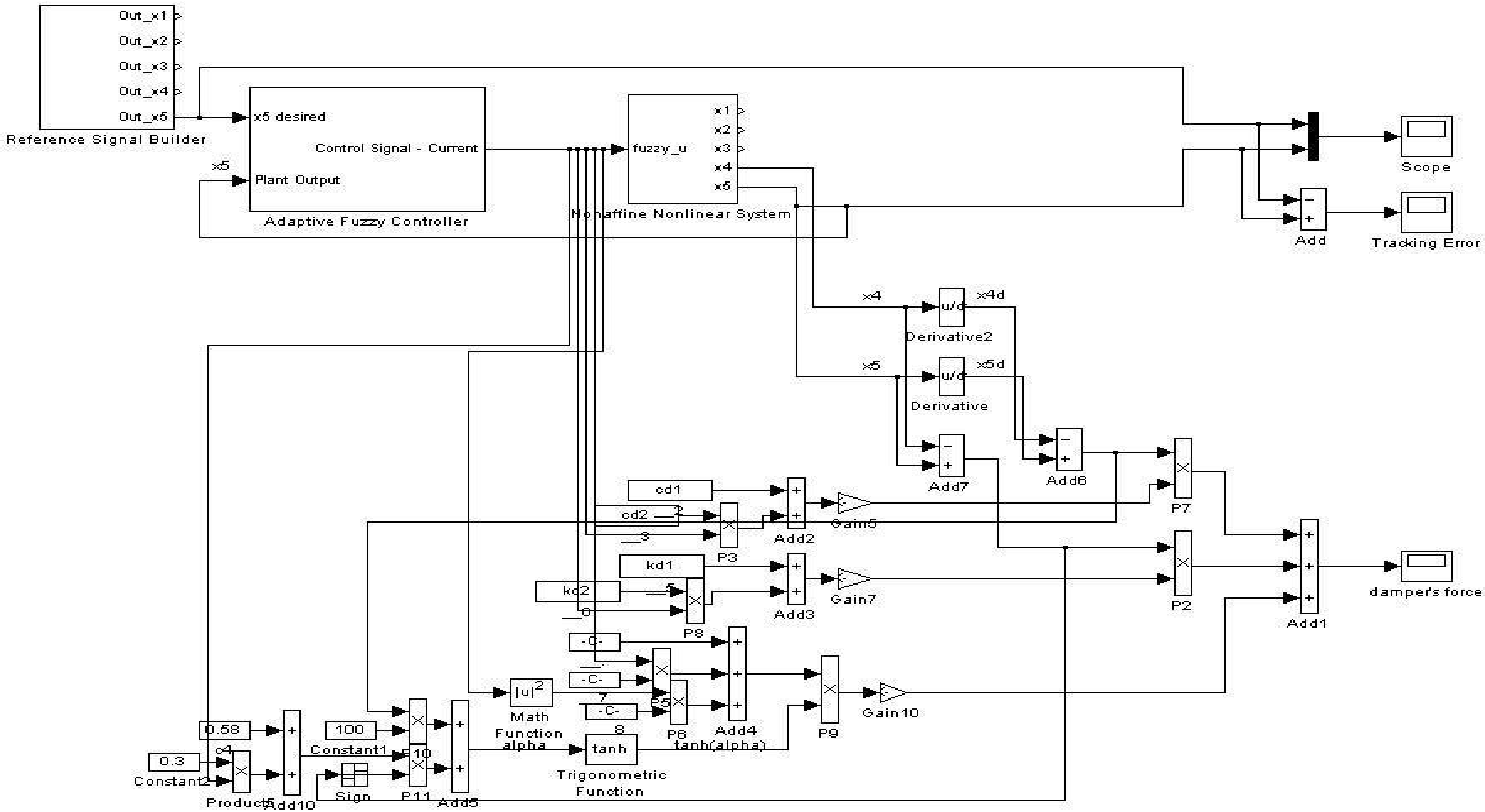


Figure 6.28. Simulink of the five storey structure

The last storey displacement time history of this particular five storey building embedded with MR dampers and self-organising adaptive fuzzy logic controller is shown in figure 6.29.

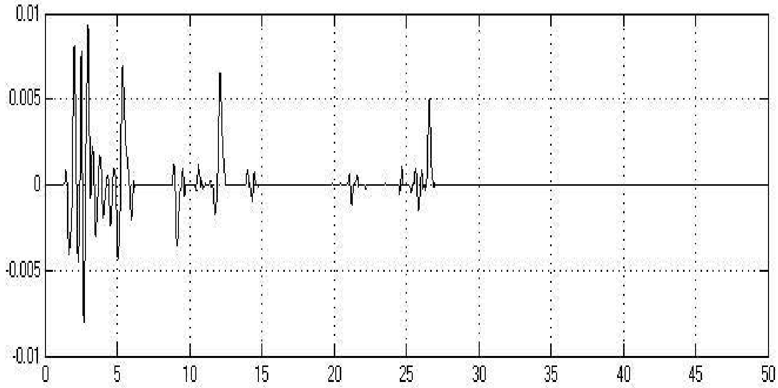


Figure 6.29. Displacement time history (m) of the fifth storey

The initial fuzzy logic controller has *8* rules with two membership function in each input dimension as shown in figure 6.30.

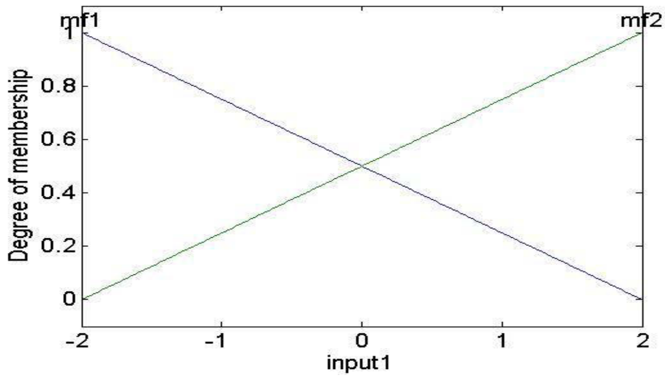


Figure 6.30. Initial membership function for all three input variables

The simulation results are shown below. A variable called *self*-organising *flag* is used to indicate when the self-organising performs. When the self-organising flag switches from *1* to -*1* or -*1* to *1*, it indicates a change in the fuzzy system structure has occurred.

It can be observed that the controller successfully controls the non-affine nonlinear system to track the reference signal. Self-organising happens in the 3^{rd} second, as shown in figure 6.34. It is in this second that the self-organising flag switches from *1* to *-1* and the number of the rules switches from *8* to *12* and remains constant to the end of the iteration procedure. The tracking error is within the range $[-0.01\ \ 0.01]$ as shown in figure 6.35. The current produced by the controller is shown in figure 6.36.

The damping force produced by the damper is the maximum of 3500 N in the 3^{rd} second, as shown in figure 6.37, which can be provided by a RD-1005-3 MR damper. Configurations of this damper are shown in table 6-7.

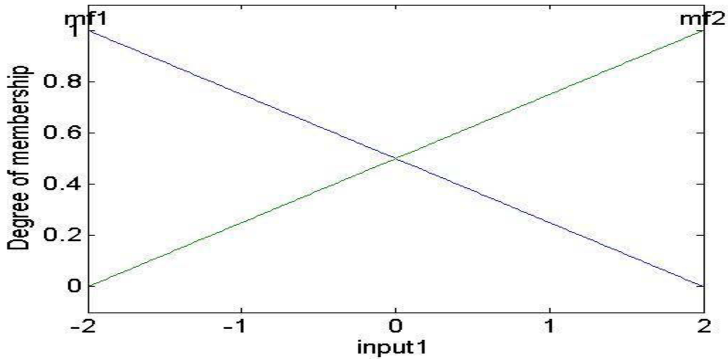


Figure 6.31. Final membership function for input 1

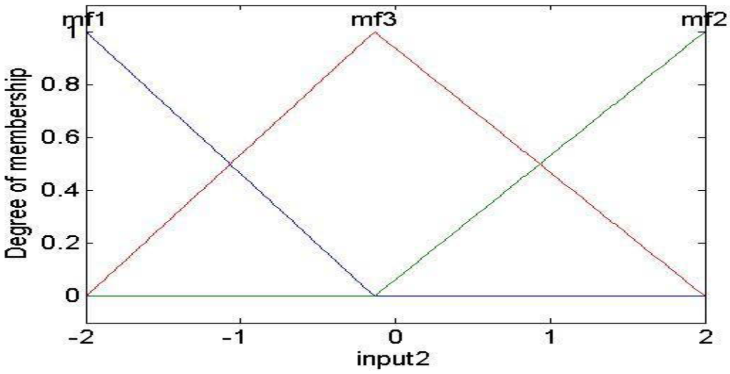


Figure 6.32. Final membership function for input 2

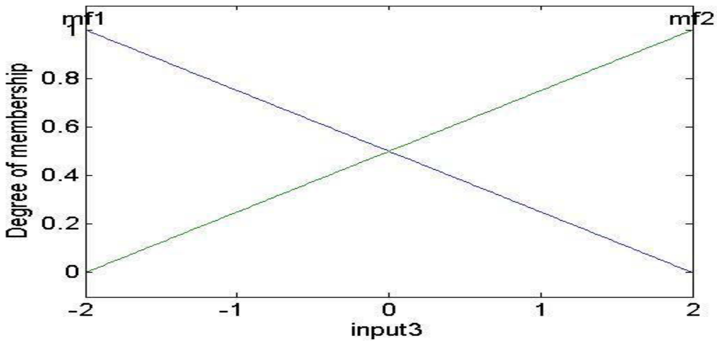


Figure 6.33. Final membership function for input 3

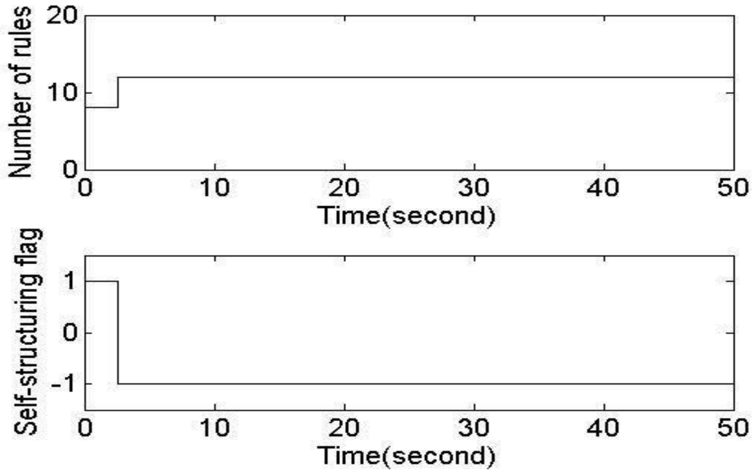


Figure 6.34. Number of rules and self-organising flag versus time

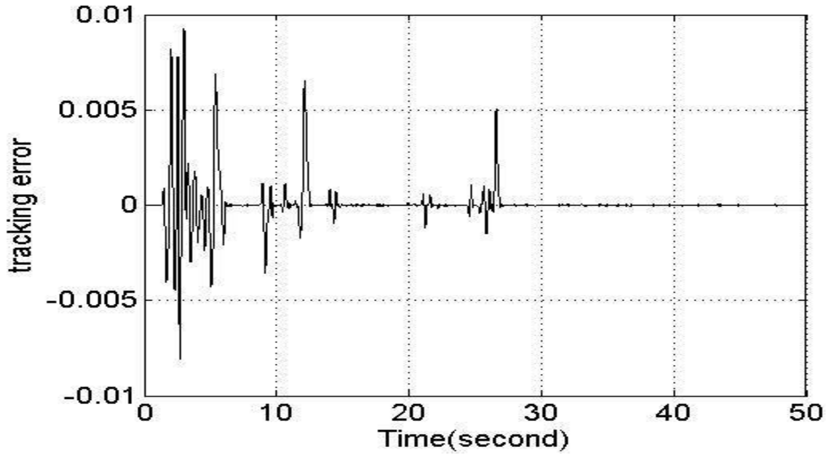


Figure 6.35. Tracking error versus time

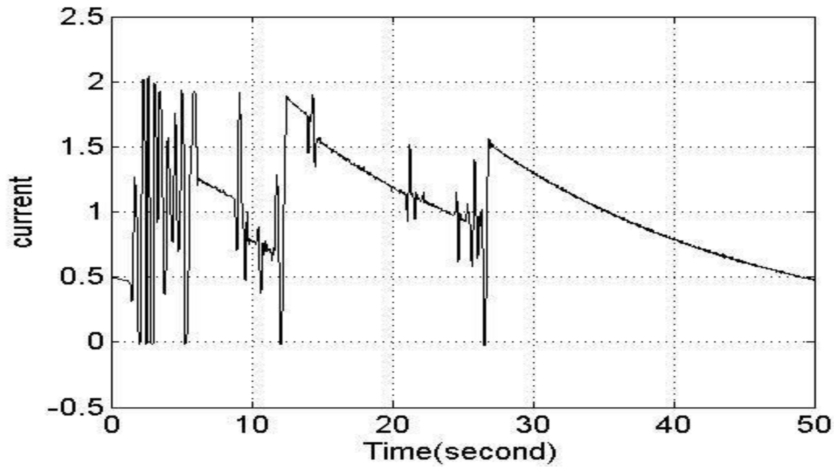


Figure 6.36. Current produced by the controller – time

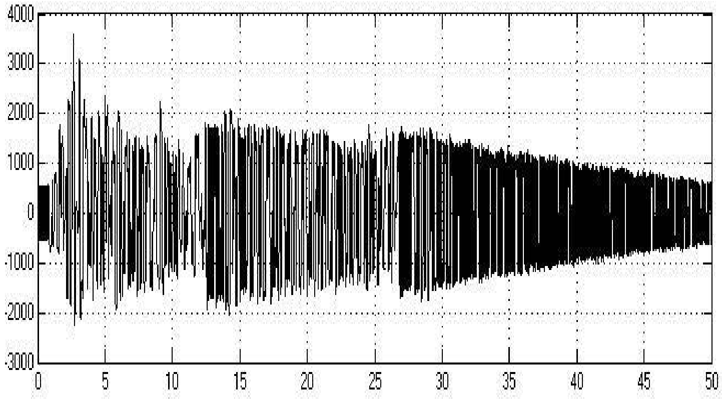


Figure 6.37. Control force provided by the MR damper

Table 6-7- Configurations of RD-1005-3 MR damper

Piston-rod movement journey	53mm
Maximal damping force	4 450 N
Maximal input voltage	12 V
Maximal electric current	2A

6.9. Evaluation criteria

The effectiveness on reductions in earthquake-induced vibrations on the building structure is further evaluated by a set of performance indices comparing the controlled response against the results obtained from the no-control cases. The criteria, adopted from (Djajakesukma, Samali & Nguyen 2002),(Ohtori et al. 2004) encompass ratios of storey displacements and accelerations.

6.10. Response ratios

The evaluation ratio for three different earthquakes, El Centro, Kobe and Northridge for a five storey structure equipped with a pair of MR dampers in between the *4th* and *5th* floors for two cases; fuzzy logic controller and self-organising adaptive fuzzy logic controller, is shown in table 6-8.

Table 6-8- Response ratios

Different Controller	Fuzzy logic controller					Self-organising adaptive fuzzy logic control				
Floor	1	2	3	4	5	1	2	3	4	5
El Centro										
J_1	0.26	0.15	0.15	0.24	0.14	0.26	0.14	0.14	0.18	0.12
J_2	1.95	1.7	1.08	1.3	0.26	0.42	0.22	0.26	0.73	0.27
J_3	0.6	0.53	0.13	0.23	0.4	0.26	0.3	0.11	0.1	0.04
J_4	0.1	0.07	0.07	0.07	0.06	0.04	0.03	0.02	0.01	0.01
J_5	0.18	0.12	0.17	0.36	0.1	0.07	0.03	0.05	0.11	0.03
J_6	0.82					0.26				
Kobe										
J_1	0.38	0.32	0.27	0.32	0.27	0.34	0.24	0.22	0.2	0.13
J_2	3.1	4.7	2.8	5.6	6.5	0.52	0.37	0.36	0.62	0.39
J_3	1.3	2.4	2.3	3.1	3.7	0.34	0.4	0.38	0.91	0.53
J_4	0.18	0.13	0.12	0.3	0.4	0.02	0.08	0.07	0.02	0.01
J_5	0.21	0.14	0.2	0.33	0.14	0.01	0.05	0.06	0.28	0.13
J_6	0.47					0.19				
Northridge										
J_1	0.27	0.15	0.17	0.34	0.17	0.22	0.12	0.16	0.26	0.15
J_2	1.4	1.8	2.8	3.1	3.8	0.41	0.18	0.28	0.52	0.21
J_3	0.27	0.3	0.03	0.05	0.09	0.12	0.03	0.01	0.04	0.07
J_4	0.3	0.5	0.5	0.4	0.6	0.05	0.02	0.06	0.03	0.04
J_5	0.19	0.22	0.3	0.32	0.45	0.13	0.11	0.16	0.24	0.28
J_6	0.47					0.19				

It is indicated for El Centro earthquake (M_w = 6.9), that the reduction in quake-induced displacements is respectively the same for both controllers. On the other hand, there is a subtle increase in the acceleration despite the ability in reducing the displacements. The self-organising adaptive fuzzy logic controller seems to be more efficient in reducing both the displacement and accelerations induced in the structure in comparison to the fuzzy logic controller. The required current for the fuzzy logic controller is four times the current required for the self-organising adaptive fuzzy logic controller.

For Kobe earthquake (M_w = 7.3), the reduction in displacement for both controllers is respectively the same. As for the acceleration, the self-organising adaptive fuzzy logic controller is more effective in comparison to the fuzzy logic controller. The required current for the fuzzy logic controller is twice the current essential for the self-organising adaptive fuzzy logic controller.

For Northridge earthquake (M_w = 6.7), the reduction in displacement for both controllers is relatively the same. The acceleration does not have a dramatic increase for the self-organising adaptive fuzzy logic controller in comparison to the fuzzy logic controller despite its effectiveness in reducing these excitations. The required current for the fuzzy logic controller is twice that required for the self-organising adaptive fuzzy logic controller.

6.11. Summary

Self-organising adaptive fuzzy logic systems are used to overcome thenon-affine nonlinear state space equations encountered when solving the equation of motion of the structure. As can be seen, the numerical simulation for self-organising adaptive fuzzy logic controller when dealing with non-affine nonlinear systems is very promising because the explicit formula of the current is not needed and this method is very generic, in the sense that it can be applied to other systems.

In addition, as mentioned earlier, fixed-structured fuzzy logic control requires designers to choose the rule base and membership functions by trial and error, which is a very time-consuming task. Therefore, self-organising adaptive fuzzy logic controller is more advantageous as it can automatically add and remove rules from a fuzzy system without the help of the intelligent user.

CHAPTER 7

THESIS CONCLUSION

7.1. Summary

This thesis has described in detail the seismic vibration suppression process in building structures subject to external excitations. As observed in the recent centuries, widespread catastrophic effects have been seen due to severe earthquakes. Damage due to such excitations can be destructive which indicates the need for more effective methods of earthquake protection.Towards the achievement of high performance smart structures, vibration control in complex civil structures has been very promising, particularly in the mitigation of external excitations and dynamic loadings owing to its advantages of low cost, robustness and reliability against various loading sources and integration of actuators, sensors, computing and signal processing units. Control performance and energy efficiency can be improved via direct input control of smart devices from the dissipation point of view by using parameterized relationships describing the damper dynamics with respect to the applied electrical signal and integrate their models into structural dynamics.

Therefore, to deal with these destructive excitations, semi-active seismic vibration suppression control has been discussed in this thesis. Magneto rheological (MR) dampers are embedded within the building structure to mitigate the seismic vibration. Fuzzy logic controllers are the control devices used in this case to produce control forces to neutralize the destructive forces of the external excitations. These two have been implemented in a one and five storey benchmark building structure and their seismic reduction capability is compared with the case when there is neither of these installed in the structure. Considerable vibration reduction has been seen and their implementation in actual building structures is effortless.

7.2. Contributions

The contributions made to this field are:

i. When ATMD (active tuned mass damper) is installed in the five and fifteen storey structure, the displacement of the last storey is estimated considering different mass ratios (= mass of ATMD / mass of structure) ranging from 1 to 4%. Both for the five and fifteen storey structure, it is observed that as the mass ratio approaches 4%, the displacement of the last storey reduces to nearly zero.

ii. The ATMD installed in the five and fifteen storey structure is located in different floors. For the five storey structure, in one case there are two ATMDs, one located on the first and one on the fifth floor. In another case, there are two ATMDs one located on the third and one on the fifth floor. The displacement of the last storey is reduced considerably in the case when there is one ATMD at the top and one in mid-height of the structure in contrast to one ATMD at the top storey and one at the first storey. For the fifteen storey structure, in one case, there are two ATMDs one located on the third floor and one at the last floor. In the second case, there are two ATMDs one located on the seventh floor and one at the last floor. In the third case, there are two ATMDs one located on the thirteenth floor and one at the last floor.

iii. Multiple ATMDs have a higher capability in mitigating the vibration induced in the structure due to earthquake excitation since they cover a wider range of frequencies compared to sole ATMDs. For the five storey structure, when 3ATMDs with equal mass are installed at the top of the structure, the reduction in the last storey displacement is more considerable compared to 3ATMDs with non-equal mass or a sole ATMD on the top floor. After the earthquake, for the free-vibration period, the 3ATMDs with equal mass have the same effect on the vibration reduction of the last storey.

iv. As the height of the structure is increased to fifteen stories, a sole ATMD on top has considerable effect on the reduction of the last storey displacement. The effect of 3ATMDs with equal mass or non-equal mass on seismic vibration reduction is not observable. Therefore multiple ATMDs are mainly effective in low-rise structures in contrast to a sole ATMD which is very efficient in high rise structures.

v. Self-organising adaptive fuzzy logic controller is the main contribution of this research. When solving the equation of motion of a building structure equipped with MR dampers and intelligent control, non-affinity and nonlinearity is encountered. Therefore, to solve these equations, self-organising adaptive fuzzy logic controllers are proposed.

vi. The considerable vibration reductions observed in this case have been compared with the case of only fuzzy logic controllers and MR dampers. Several evaluation criteria have been introduced which indicate the amount of seismic vibration reduction when self-organising adaptive fuzzy logic controllers are applied in comparison to fuzzy logic controllers.

vii. The limitations encountered in using self-organising adaptive fuzzy logic controllers proposed in this research, is the membership functions which can only acquire a triangular shape. Therefore, in case other types of membership functions required, the MATLAB codes provided is not applicable. Another limitation is when the structure becomes nonlinear, the control algorithm which cannot distinguish the nonlinearity in the structural parameters (mass, stiffness and damping) as MATLAB is only a numerical software used here for the control algorithm and not a Structural Engineering software.

7.3. Direction for future work

To enhance the findings of this research, several suggestions are listed as follows:

i. The experimental implementation can be done and different design scenarios can be compared. In addition to this, other control algorithms could be proposed to deal with the non-affine nonlinear state space equations encountered when implementing these semi-active vibration control devices due to external excitations.

ii. A high-rise building structure could be considered, e.g. the 76 storey benchmark building (Samali et al.) the model reduction methods could be used to simplify the simulation procedure. The performance of this structure could be checked, due to wind excitations as the external excitations subjected on the structure and the performance of the aforementioned structures could be compared with different design scenarios or uncontrolled cases or any other control algorithm defined.

7.4. Conclusion

Active tuned mass dampers are installed in the five and fifteen storey structures; the displacement of the last storey is estimated considering different mass ratios. As the mass of the ATMD increases from 1 to 4% the effect on the seismic reduction of displacement due to El Centro earthquake is very considerable. When two ATMDs are each installed in different levels of the structure, a considerable seismic reduction is observed when one ATMD is installed on mid-height and one at the top of the structure, especially in low-rise structures. ATMDs are not as effective in seismic vibration reduction as a sole ATMD in high-rise structures which are prone to external excitation.

Self-organising adaptive fuzzy logic controllers have been introduced in this research work. It has been shown that these types of intelligent controllers are more effective than fuzzy logic controllers in terms of seismic vibration reduction of building structures, as shown in the previous chapter. In addition, fuzzy logic controllers have a fixed structure after the intelligent user has defined the membership functions by trial and error. Since mathematical modeling of different plants requires knowledge on the plant and this may not be accessible, the trial and error process for rule defining is very time-consuming. Self-organising adaptive fuzzy logic controllers are advantageous as they can automatically add and remove rules to a fuzzy inference system.

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APPENDIX

APPENDIX A

PROOF OF LEMMA 3 IN CHAPTER 5

Step1: Let $\underline{X}^j$ is a point in set$U_{\underline{X}}$: $\underline{X}^j \in U_{\underline{X}}$. Since $f(\underline{x}, u(\underline{X}))$ is continuous with respect to $u(\underline{X})$, according to the Mean Value Theorem, there exists a positive constant $c^j > 0$ such that

$$f\left(\underline{x}^j, u^*(\underline{X}^j)\right) - f\left(\underline{x}^j, u(\underline{X}^j)\right) = c^j(u^*(\underline{X}^j) - u(\underline{X}^j)) \quad \text{(A.1)}$$

Since $f\left(\underline{x}^j, u^*(\underline{X}^j)\right) - f\left(\underline{x}^j, u(\underline{X}^j)\right)$ is continuous at $\underline{X}^j$, for each dimension $i = 1, \dots, n, n+1$ there exists a constant $\delta_i{}^j > 0$ such that

$$|\mathrm{X_i} - \mathrm{X_i}^{\mathrm{j}}| < \delta_{\mathrm{i}}{}^{\mathrm{j}} \Leftrightarrow \left|\left[\mathrm{f}\left(\underline{\mathrm{x}}, \mathrm{u}^*(\underline{\mathrm{X}})\right) - \mathrm{f}\left(\underline{\mathrm{x}}, \mathrm{u}(\underline{\mathrm{X}})\right)\right] - [\mathrm{f}\left(\underline{\mathrm{x}}^{\mathrm{j}}, \mathrm{u}^*(\underline{\mathrm{X}}^{\mathrm{j}})\right) - \mathrm{f}\left(\underline{\mathrm{x}}^{\mathrm{j}}, \mathrm{u}(\underline{\mathrm{X}}^{\mathrm{j}})\right)]\right| \le \varepsilon^* \quad \text{(A.2)}$$

Substituting (A.1) to (A.2) gives

$$|\mathrm{X_i} - \mathrm{X_i}^{\mathrm{j}}| < \delta_{\mathrm{i}}{}^{\mathrm{j}} \Leftrightarrow \left|\left[\mathrm{f}\left(\underline{\mathrm{x}}, \mathrm{u}^*(\underline{\mathrm{X}})\right) - \mathrm{f}\left(\underline{\mathrm{x}}, \mathrm{u}(\underline{\mathrm{X}})\right)\right] - c^j[\mathrm{u}^*(\underline{\mathrm{X}}^j) - \mathrm{u}(\underline{\mathrm{X}}^j)]\right| \le \varepsilon^* \quad \text{(A.3)}$$

In which $c^j > 0$.

In other words, (A.3) implies that for every point $\underline{X}^j \in U_{\underline{X}}$ there exists a non-empty set $O_j = \{\underline{X} \parallel |\mathrm{X_i} - \mathrm{X_i}^{\mathrm{j}}| < \delta_{\mathrm{i}}{}^{\mathrm{j}}\}$, $i = 1, \dots, n+1$, such that $\mathrm{f}\left(\underline{\mathrm{x}}, \mathrm{u}^*(\underline{\mathrm{X}})\right) - \mathrm{f}\left(\underline{\mathrm{x}}, \mathrm{u}(\underline{\mathrm{X}})\right)$ can be approximated by $c^j[\mathrm{u}^*(\underline{\mathrm{X}}^j) - \mathrm{u}(\underline{\mathrm{X}}^j)]$ with an arbitrary accuracy ε^*.

As $U_{\underline{X}}$ is compact, there exists a finite M points $\underline{X}^j \in U_{\underline{X}}$, dimension $j = 1, \dots, M$ such that

$$U_{\underline{X}} \subseteq O_1 \cup O_1 \cup \dots \cup O_M \quad \text{(A.4)}$$

Step 2: Now, consider a fuzzy system with M rules centered at $\underline{X}^j$, $j = 1, \dots, M$, satisfying (A.3) and (A.4). The membership function of rule j, in dimension i,

$A_i{}^j(X_i) = \propto (X_i{}^j - \delta_i{}^j, X_i{}^j + \delta_i{}^j)(X_i)$, $i = 1, \dots, n+1$, $j = 1, \dots, n$, are chosen such that

$$\begin{cases} A_i{}^j(X_i{}^k) \neq 0 & if \underline{X} \in O_j \\ A_i{}^j(X_i{}^k) = 0 & if \underline{X} \notin O_j \end{cases} \quad \text{(A.5)}$$

For example, a triangular membership function with end points at ${X_i}^j - {\delta_i}^j$ and ${X_i}^j + {\delta_i}^j$, is satisfied (A.5).

Step 3: Now, we will show the above fuzzy system guarantee that $\mathrm{f}\left(\underline{\mathrm{x}}, \mathrm{u}^*(\underline{\mathrm{X}})\right) - \mathrm{f}\left(\underline{\mathrm{x}}, \mathrm{u}(\underline{\mathrm{X}})\right) = \sum_{j=1}^{M} c^j\left({\theta_j}^* - \theta_j\right)\zeta_j\left(\underline{\mathrm{X}}\right) + \varepsilon$ In which $|\varepsilon| \le \varepsilon^*$ and c^j are some positive constants.

From (A.5), we have

$$\begin{cases} \mu_j(\underline{\mathrm{X}}) = \prod_{j=1}^{n} {A_i}^j(X_i) \neq 0 \quad if\,\underline{X} \in O_j \\ \mu_j(\underline{\mathrm{X}}^k) = \prod_{j=1}^{n} {A_i}^j({X_i}^k) = 0 \quad if\,\underline{X} \notin O_j \end{cases}$$

And

$$\begin{cases} \zeta_j(\underline{\mathrm{X}}^k) = \dfrac{\mu_j(\underline{\mathrm{X}}^k)}{\sum_{i=1}^{M} \mu_j(\underline{\mathrm{X}}^k)} = 1 \quad if\,\underline{X} \in O_j \\ \zeta_j(\underline{\mathrm{X}}^k) = \dfrac{\mu_j(\underline{\mathrm{X}}^k)}{\sum_{i=1}^{M} \mu_j(\underline{\mathrm{X}}^k)} = 0 \quad if\,\underline{X} \notin O_j \end{cases}$$

Therefore,

$$\mathrm{u}(\underline{\mathrm{X}}^j) = \sum_{k=1}^{M} \theta_k\, \zeta_k(\underline{\mathrm{X}}^j) = \theta_1 \times 0 + \cdots + \theta_j \times 1 + \cdots + \theta_M \times 0 = \theta_j \tag{A.6}$$

and

$$\mathrm{u}^*(\underline{\mathrm{X}}^j) = \sum_{k=1}^{M} {\theta_k}^*\, \zeta_k(\underline{\mathrm{X}}^j){\theta_j}^* \tag{A.7}$$

Substituting (A.6) and (A.7) to (A.3), we have:

$$\left|X_i - {X_i}^j\right| < {\delta_i}^j \Leftrightarrow \left|\left[f\left(\underline{x}, \mathrm{u}^*(\underline{X})\right) - f\left(\underline{x}, u(\underline{X})\right)\right] - c^j({\theta_j}^* - \theta_j)\right| \le \varepsilon^* \text{(A.8)}$$

As $\zeta_j(\underline{X}) \neq 0$ for $\underline{X} \in O_j$ and

$\zeta_j(\underline{X}) = 0$ for $\underline{X} \notin O_j$, from (A.8) we have:

$$\left|\left[f\left(\underline{x}, \mathrm{u}^*(\underline{X})\right) - f\left(\underline{x}, u(\underline{X})\right)\right] - c^j({\theta_j}^* - \theta_j)\right| \zeta_j(\underline{X}) \le \varepsilon^*\, \zeta_j(\underline{X})\, , \forall \underline{X} \in U_{\underline{X}}$$

Take the summation for $j = 1, \dots, M$,

$$\sum_{j=1}^{M} \left|\left[f\left(\underline{x}, \mathrm{u}^*(\underline{X})\right) - f\left(\underline{x}, u(\underline{X})\right)\right] - c^j({\theta_j}^* - \theta_j)\right| \zeta_j(\underline{X}) \le \sum_{j=1}^{M} \varepsilon^*\, \zeta_j(\underline{X}), \forall \underline{X} \in U_{\underline{X}}$$

which is equivalent to

$$\left|\left[f\left(\underline{x},\mathrm{u}^*(\underline{X})\right)-f\left(\underline{x},u(\underline{X})\right)\right]\sum_{j=1}^{M}\zeta_j(\underline{X})-c^j(\theta_j{}^*-\theta_j)\sum_{j=1}^{M}\zeta_j(\underline{X})\right|\leq\varepsilon^*\sum_{j=1}^{M}\zeta_j(\underline{X})$$

$$\forall\underline{X}\in U_{\underline{X}}$$

Since $\sum_{j=1}^{M}\zeta_j(\underline{X})=1,\forall\underline{X}\in U_{\underline{X}}$, we have:

$$\left|\left[f\left(\underline{x},\mathrm{u}^*(\underline{X})\right)-f\left(\underline{x},u(\underline{X})\right)\right]-c^j(\theta_j{}^*-\theta_j)\sum_{j=1}^{M}\zeta_j(\underline{X})\right|\leq\varepsilon^*$$

which is equivalent to

$$\left|\left[f\left(\underline{x},\mathrm{u}^*(\underline{X})\right)-f\left(\underline{x},u(\underline{X})\right)\right]\sum_{j=1}^{M}\zeta_j(\underline{X})-c^j(\theta_j{}^*-\theta_j)\sum_{j=1}^{M}\zeta_j(\underline{X})\right|\leq\varepsilon^*\sum_{j=1}^{M}\zeta_j(\underline{X})$$

$$\forall\underline{X}\in U_{\underline{X}}$$

Since$\sum_{j=1}^{M}\zeta_j(\underline{X})=1,\forall\underline{X}\in U_{\underline{X}}$, we have:

$$\left|\left[f\left(\underline{x},\mathrm{u}^*(\underline{X})\right)-f\left(\underline{x},u(\underline{X})\right)\right]-c^j(\theta_j{}^*-\theta_j)\sum_{j=1}^{M}\zeta_j(\underline{X})\right|\leq\varepsilon^*$$

APPENDIX B

MATLAB CODES FOR ONE STOREYSTRUCTURE

```
%*************************************************************************
clc                            % ONE STOREY STRUCTURE
%*************************************************************************
% EQUIPPED WITH A PAIR OF MR DAMPERS ON THE LAST FLOOR
% DUE TO ELCENTRO QUAKE (normalised to 2g) WITH A FUZZY LOGIC CONTROLLER
%                         *******************
% THE FUZZY LOGIC CONTROLLER INPUTS :
%   x1(RELATIVE DISP OF 1ST FLOORS) +  v1 (RELATIVE VELO OF 1ST FLOORS)
% THE FUZZY LOGIC CONTROLLER OUTPUT :
%   i (CURRENT).
%                         *******************
% THE MR DAMPER CHARACTERISTICS ARE:
alpha2=-488;alpha1=1836;alpha0=64;beta1=100;delta11=0.3;delta10=0.58;
kd1=10200;kd2=-3400;cd1=2464;cd2=3858;
%                         *******************
% THE FIVE STOREY STRUCTURE'S CHARACTERISTICS ARE:
% f=4; % f is the fundamental frequency of the structure (Hz)
% f(quake)=1.5; % f is the fundamental frequency of the earthquake (Hz)
% saay=2; % saay is the critical damping
m1=1000;% m in N.
k1=576000;% k in N/m.
c1=100000;% c in Ns/m.

%                         *******************
% THE CURRENT(i) IS THE OUTPUT OF THE FUZZY LOGIC CONTROLLER
% THE INPUT TO THE MR DAMPER :  0 < i < imax = 2A
%                         *******************
%                                 PLOT
```

```
%                          ******************
h=plot(x1con,'red');
hold on
hh=plot(x1uncon);
set(h,{'DisplayName'},{'x1con(m)'}')
set(hh,{'DisplayName'},{'x1uncon(m)'}')
legend show
%ii=plot(i,'red');
%set(q,{'DisplayName'},{'current(i)'}')
%legend show
%
%det([k]-(w^2)*[m])=0
%
```

```
function [fuzzy_output,indicator1] =
structure_learning(z,fuzzy_input,error,structure_learning_params,current_ou
tput)

% This function performs structure learning of the fuzzy system. This
% function can only be used for rectangular-mf fuzzy systems.
%
% error is the output error or tracking error

% current output is the current value of the fuzzy system output

% mf_threshold is a threshold that a new mf is considered if the max mf
% degree in any input dimension is smaller than this value

% error_threshold is a threshold that a new mf is considered if the output
% error (or tracking error) is smaller than this value

% a0 is the matrix specifies the 1/2 the maximum predefined spreads of
% rectangular mfs in each dimension

% mf_degree_threshold (which characterizes the similarity between the mf
center and the input) is the threshold that a mf should be
% replaced by a new one if the mf degree of the input is larger or equal to
this
% value
mf_threshold = structure_learning_params.mf_threshold;
error_threshold = structure_learning_params.error_threshold;
a0 = structure_learning_params.a0;
center_distance_threshold =
structure_learning_params.center_distance_threshold;
max_N_rules = structure_learning_params.max_N_rules;

persistent indicator

if isempty(indicator)
   indicator = 1;
end

%==========initialize the first rule to the first input entered======

% =====================================================================
% ======= Part 3================
```

```
if abs(error) >= error_threshold % then a new mf is added or replaced


% Determine the most firing rule

[most_firing_rule_strength,most_firing_rule_index]=max(current_output.ARR);

% The result of evaluating input values through mfs of the most firing rule
    mf_degree_vector = current_output.IRR(most_firing_rule_index,:); %
mf_degree_vector contains the result of evaluating input
% values through mfs of the most firing rule


% Determine the dimension in which the max mf degree obtains
    [max_mf_degree,var_index] = max(mf_degree_vector);% var_index2 is the
dimension in which max mf degree obtains

% Determine new_N_rules would be reached when adding one more mf.
    Num_Input_MFs = getfis(fuzzy_input,'NumInputMFs');
    new_Num_Input_MFs = Num_Input_MFs;
    new_Num_Input_MFs(var_index) = Num_Input_MFs(var_index)+1;
    new_N_rules = prod(new_Num_Input_MFs);

% Determine if a new mf should be considered based on the similarity
% measure. If center_distance is smaller than center_distance_threshold, a
new rule
% should not be added.
    most_activated_mf_index = 0;
    Rulelist = getfis(fuzzy_input,'Rulelist');
    most_activated_mf_index = Rulelist(most_firing_rule_index,var_index);
    most_activated_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',most_activated_mf_index,'params')
;
    center_distance = abs(z(var_index)-most_activated_mf_params(2));

    similarity_measure = 1;
if center_distance<center_distance_threshold(var_index)
        similarity_measure = 1; % "1" represents "similar"
else
        similarity_measure = 0; % "0" represents "not similar"
end

if (similarity_measure == 0)&&(new_N_rules > max_N_rules) % replace a mf by
a new one

% Determine the mf_to_be_replaced which is the farest mf
        farest_mf_index = 0;
        max_abs_distance = 0;
for i=1:getfis(fuzzy_input,'input',var_index,'nummfs')
            current_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
            distance = current_params(2)-z(var_index);
if abs(distance)>max_abs_distance
                max_abs_distance = abs(distance);
                farest_mf_index = i;
end
end
        mf_to_be_replaced_index = farest_mf_index;
```

```
% Determine the left, right mfs
        left_mf_index = 0;
        right_mf_index = 0;
        min_left_distance = -4;
        min_right_distance = 4;
for i=1:getfis(fuzzy_input,'input',var_index,'nummfs')
            current_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
            distance = current_params(2)-z(var_index);
if (distance<0) && (distance>min_left_distance) && (i ~=
mf_to_be_replaced_index)
                min_left_distance = distance;
                left_mf_index = i;
end
if (distance>0) && (distance<min_right_distance) && (i ~=
mf_to_be_replaced_index)
                min_right_distance = distance;
                right_mf_index = i;
end
end


% Replace the mf_to_be_replaced by a new one
fuzzy_input =
replace_mf_and_rules(fuzzy_input,var_index,a0,left_mf_index,z(var_index),ri
ght_mf_index,mf_to_be_replaced_index,current_output.output);
        indicator =indicator*(-1);
end

if (similarity_measure == 0)&&(new_N_rules <= max_N_rules) % then add a new
mf

% Determine the left, right mfs
        left_mf_index = 0;
        right_mf_index = 0;
        min_left_distance = -4;
        min_right_distance = 4;
for i=1:getfis(fuzzy_input,'input',var_index,'nummfs')
            current_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
            distance = current_params(2)-z(var_index);
if (distance<0) && (distance>min_left_distance)
                min_left_distance = distance;
                left_mf_index = i;
end
if (distance>0) && (distance<min_right_distance)
                min_right_distance = distance;
                right_mf_index = i;
end
end

fuzzy_input =
add_mf_and_rules(fuzzy_input,var_index,a0,left_mf_index,z(var_index),right_
mf_index,current_output.output);
        indicator =indicator*(-1);
end
else
% ====================Part 1====================

if getfis(fuzzy_input,'NumRules')>1
```

```
        [IRR_max,rule_index_vector] = max(current_output.IRR);          %
IRR_max is the vector of the max values of inputs through membership
% functions in each dimension
% rule_index_vector is the vector containing indexes of rules that max
values
% of inputs through mfs achieve in each dimension.
        [min_IRR_max,var_index] = min(IRR_max);          % min_IRR_max is
the min value of IRR_max.
% var_index is the dimension which the min value of IRR_max achieves
        rule_index = rule_index_vector(var_index);       % rule_index is the
index of rule that min value of IRR_max achieves
else
        rule_index = 1;
        [min_IRR_max,var_index] = min(current_output.IRR);
end
    Rulelist = getfis(fuzzy_input,'Rulelist');
    mf_index = Rulelist(rule_index,var_index);       % mf_index indicates
the membership function which the min value archieves


% ====================Part 2====================
if min_IRR_max<mf_threshold % then a new mf is added or replaced to either
sides

% add 1 rectangular mf in var_index dimension. This script can only be
% used for rectangular mfs, it needs modification to be used for
% gaussian membership functions

% Determine new_N_rules would be reached when adding one more mf.
        Num_Input_MFs = getfis(fuzzy_input,'NumInputMFs');
        new_Num_Input_MFs = Num_Input_MFs;
        new_Num_Input_MFs(var_index) = Num_Input_MFs(var_index)+1;
        new_N_rules = prod(new_Num_Input_MFs);

if new_N_rules > max_N_rules % then we need to replace an existing mf by a
new mf

% Determine the farest mf
            farest_mf_index = 0;
            max_abs_distance = 0;
for i=1:getfis(fuzzy_input,'input',var_index,'nummfs')
                current_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
                distance = current_params(2)-z(var_index);
if abs(distance)>=max_abs_distance
                    max_abs_distance = abs(distance);
                    farest_mf_index = i;
end
end
            mf_to_be_replaced_index = farest_mf_index;

% Determine the left, right, excluding the mf_to_be_replaced
            left_mf_index = 0;
            right_mf_index = 0;
            min_left_distance = -4;
            min_right_distance = 4;
            center = 0;
for i=1:getfis(fuzzy_input,'input',var_index,'nummfs')
                current_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
```

```
                distance = current_params(2)-z(var_index);
if (distance<0) && (distance>min_left_distance) && (i ~=
mf_to_be_replaced_index)
                    min_left_distance = distance;
                    left_mf_index = i;
                    left_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
                    center = left_mf_params(3);
end
if (distance>0) && (distance<min_right_distance) && (i ~=
mf_to_be_replaced_index)
                    min_right_distance = distance;
                    right_mf_index = i;
                    right_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
                    center = right_mf_params(1);
end
end

fuzzy_input =
replace_mf_and_rules(fuzzy_input,var_index,a0,left_mf_index,center,right_mf
_index,mf_to_be_replaced_index,current_output.output);

% Set indicator = 1 or -1 if this case occurs
            indicator = indicator*(-1);


else%add a new mf and add rules

% Determine the left, right mfs
            left_mf_index = 0;
            right_mf_index = 0;
            min_left_distance = -4;
            min_right_distance = 4;
for i=1:getfis(fuzzy_input,'input',var_index,'nummfs')
                current_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
                distance = current_params(2)-z(var_index);
if (distance<0) && (distance>min_left_distance)
                    min_left_distance = distance;
                    left_mf_index = i;
                    left_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
                    center = left_mf_params(3);
end
if (distance>0) && (distance<min_right_distance)
                    min_right_distance = distance;
                    right_mf_index = i;
                    right_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
                    center = right_mf_params(1);
end
end

fuzzy_input =
add_mf_and_rules(fuzzy_input,var_index,a0,left_mf_index,z(var_index),right_
mf_index,current_output.output);
            indicator =indicator*-1;
end
```

```
% Recalculate the output after the fuzzy system changes
% [output, IRR, ORR, ARR]= evalfis(z,fuzzy_input);

end
end


fuzzy_output = fuzzy_input;
indicator1 = indicator;

%============================================================================

functionfuzzy_output =
replace_mf_and_rules(fuzzy_input,var_index,a0,left_mf_index,center,right_mf
_index,mf_to_be_replaced_index,initial_value)

% Modify the mf neibouring to the farest mf (it is either left or right
neibouring mf)

% Determine the neibouring mf of the farest mf
    farest_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',mf_to_be_replaced_index,'params')
;
    left_farest_mf_index = 0;
    right_farest_mf_index = 0;
    min_left_farest_distance = -4;
    min_right_farest_distance = 4;
for i=1:getfis(fuzzy_input,'input',var_index,'nummfs')
        current_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
        distance = current_params(2)-farest_mf_params(2);
if (distance<0) && (distance>min_left_farest_distance)
            min_left_farest_distance = distance;
            left_farest_mf_index = i;
end
if (distance>0) && (distance<min_right_farest_distance)
            min_right_farest_distance = distance;
            right_farest_mf_index = i;
end
end

% Modify the left param if the neibouring mf of the farest mf is on the
left
if left_farest_mf_index ~= 0
        left_farest_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',left_farest_mf_index,'params');
        left_farest_mf_params(3) = left_farest_mf_params(2)+a0(var_index);
fuzzy_input =
setfis(fuzzy_input,'input',var_index,'mf',left_farest_mf_index,'params',lef
t_farest_mf_params);
end

% Modify the right param if the neibouring mf of the farest mf is on the
right
if right_farest_mf_index ~= 0
        right_farest_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',right_farest_mf_index,'params');
        right_farest_mf_params(1) = right_farest_mf_params(2)-
a0(var_index);
```

```
fuzzy_input =
setfis(fuzzy_input,'input',var_index,'mf',right_farest_mf_index,'params',ri
ght_farest_mf_params);
end

% modify the neibourhood mfs of the new added mf if there exist ones
if left_mf_index ~= 0
    left_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',left_mf_index,'params');
    left_mf_params(3) = center;
fuzzy_input =
setfis(fuzzy_input,'input',var_index,'mf',left_mf_index,'params',left_mf_pa
rams);
end

if right_mf_index ~= 0;
    right_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',right_mf_index,'params');
    right_mf_params(1) = center;
fuzzy_input =
setfis(fuzzy_input,'input',var_index,'mf',right_mf_index,'params',right_mf_
params);
end

% Determine the params of the new mf
if left_mf_index == 0
    new_mf_params(1) = center-a0(var_index);
else
    new_mf_params(1)= left_mf_params(2);
end
    new_mf_params(2) = center;
if right_mf_index == 0
    new_mf_params(3) = center+a0(var_index);
else
    new_mf_params(3)= right_mf_params(2);
end

% Replace the farest mf by a new mf and initialize all the related rules to
the current output
fuzzy_input =
setfis(fuzzy_input,'input',var_index,'mf',mf_to_be_replaced_index,'params',
new_mf_params);

% Initialize all the related rules to the current output
Rulelist = getfis(fuzzy_input,'Rulelist');
for i=1:getfis(fuzzy_input,'NumRules')
if Rulelist(i,var_index)==mf_to_be_replaced_index
fuzzy_input = setfis(fuzzy_input,'output',1,'mf',i,'params',initial_value);
end
end



fuzzy_output = fuzzy_input;

functionfuzzy_output =
add_mf_and_rules(fuzzy_input,var_index,a0,left_mf_index,center,right_mf_ind
ex,initial_value)
```

```
% modify the neibourhood mfs if there exist ones
if left_mf_index ~= 0
    left_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',left_mf_index,'params');
    left_mf_params(3) = center;
fuzzy_input =
setfis(fuzzy_input,'input',var_index,'mf',left_mf_index,'params',left_mf_pa
rams);
end

if right_mf_index ~= 0;
    right_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',right_mf_index,'params');
    right_mf_params(1) = center;
fuzzy_input =
setfis(fuzzy_input,'input',var_index,'mf',right_mf_index,'params',right_mf_
params);
end

% Determine the params of the new mf
if left_mf_index == 0
    new_mf_params(1) = center-a0(var_index);
else
    new_mf_params(1)= left_mf_params(2);
end
    new_mf_params(2) = center;
if right_mf_index == 0
    new_mf_params(3) = center+a0(var_index);
else
    new_mf_params(3)= right_mf_params(2);
end

% Add a new mf
added_mf_index = getfis(fuzzy_input,'input',var_index,'Nummfs')+1; % the
index indicates the new mf
mf_name = strcat('mf',num2str(added_mf_index));
fuzzy_input =
addmf(fuzzy_input,'input',var_index,mf_name,'trimf',new_mf_params);

% Add rules using generate_rules function
fuzzy_input=generate_rules(fuzzy_input,var_index,added_mf_index,initial_val
ue);

fuzzy_output = fuzzy_input;
```

```
function SOAFS(block)

setup(block);

function setup(block)

    block.NumDialogPrms     = 3;
```

```
% get the initial number of adaptive parameters = number of rules
fuzzy_u = block.DialogPrm(1).Data;
% AFS_params = block.DialogPrm(2).Data;
     structure_learning_params = block.DialogPrm(3).Data;
% no_of_rules = getfis(fuzzy_u,'NumRules');

    block.NumInputPorts  = 2;
    block.NumOutputPorts = 3;

    block.SetPreCompInpPortInfoToDynamic;
    block.SetPreCompOutPortInfoToDynamic;

    block.InputPort(1).Complexity   = 'Real';
    block.InputPort(1).DataTypeId   = 0;
    block.InputPort(1).SamplingMode = 'Sample';
    block.InputPort(1).Dimensions   = 1;

    block.InputPort(2).Complexity   = 'Real';
    block.InputPort(2).DataTypeId   = 0;
    block.InputPort(2).SamplingMode = 'Sample';
    block.InputPort(2).Dimensions   = getfis(fuzzy_u,'NumInputs');

    block.OutputPort(1).Complexity   = 'Real';
    block.OutputPort(1).DataTypeId   = 0;
    block.OutputPort(1).SamplingMode = 'Sample';
    block.OutputPort(1).Dimensions   = 1;

    block.OutputPort(2).Complexity   = 'Real';
    block.OutputPort(2).DataTypeId   = 0;
    block.OutputPort(2).SamplingMode = 'Sample';
    block.OutputPort(2).Dimensions   =
structure_learning_params.max_N_rules;

    block.OutputPort(3).Complexity   = 'Real';
    block.OutputPort(3).DataTypeId   = 0;
    block.OutputPort(3).SamplingMode = 'Sample';
    block.OutputPort(3).Dimensions   = 2;

    block.SampleTimes = [0 0];

    block.RegBlockMethod('Start', @Start);
    block.RegBlockMethod('Outputs', @Outputs);
    block.RegBlockMethod('Derivatives', @Derivatives);
    block.RegBlockMethod('Terminate', @Terminate);

% set the block' number of continuous states
    block.NumContStates=structure_learning_params.max_N_rules;

%end setup function

function Start(block)

globalfuzzy_u;
fuzzy_u= block.DialogPrm(1).Data;
  no_of_rules = getfis(fuzzy_u,'NumRules');

% initialize the continuous state vector
 output_params= getfis(fuzzy_u,'OutMFParams');
```

```
 block.ContStates.Data(1:length(output_params)) = output_params(:,1);

%end function

function Outputs(block)

globalfuzzy_u
%fuzzy_u = block.DialogPrm(1).Data;
no_of_rules = getfis(fuzzy_u,'NumRules');

X=block.InputPort(2).data;

inRange = getfis(fuzzy_u,'inRange');
X=saturation_ppa(X,inRange); % see function saturation_ppa in "my m files"
for instructions

x = block.ContStates.Data(1:no_of_rules);


fuzzy_u=setfis(fuzzy_u,'OutMFParams',x);

[current_output.output, current_output.IRR, current_output.ORR,
current_output.ARR]= evalfis(X,fuzzy_u);


block.OutputPort(1).Data = current_output.output;
block.OutputPort(2).Data(1:no_of_rules) = x;

[fuzzy_u,indicator1] =
structure_learning(X,fuzzy_u,block.InputPort(1).data,block.DialogPrm(3).Dat
a,current_output);

block.OutputPort(3).Data(1) = indicator1;
block.OutputPort(3).Data(2) = getfis(fuzzy_u,'NumRules');
%endfunction

function Derivatives(block)

globalfuzzy_u;
%fuzzy_u = block.DialogPrm(1).Data;
E=block.InputPort(1).data; % the first input is the error(adaptive signal);

X=block.InputPort(2).data; % the other inputs are the state vector of the
system
inRange = getfis(fuzzy_u,'inRange');
X=saturation_ppa(X,inRange); % see function saturation_ppa in "my m files"
for instructions

%fuzzy_u = block.DialogPrm(1).Data;
AFS_params = block.DialogPrm(2).Data;
gamma  = AFS_params.gamma;
sigma  = AFS_params.sigma;
theta_U = AFS_params.theta_U;
theta_L = AFS_params.theta_L;
theta_0 = AFS_params.theta_0;
```

```
% structure_learning_params = block.DialogPrm(3).Data;
% fuzzy_u = structure_learning(X,fuzzy_u,E,block.DialogPrm(3).Data);


x= getfis(fuzzy_u,'OutMFParams');

%outRange = [theta_L theta_U];
%x = saturation_ppa2(x,outRange);

block.ContStates.Data(1:length(x(:,1))) = x(:,1);



[a,b,c,d]=evalfis(X,fuzzy_u);

if sum(d)==0,
    J=zeros(length(d),1);
else
    J = d/sum(d);
end


for i=1:length(x(:,1))
if [(x(i)>=theta_U)&(gamma*E*J(i)>=sigma*(x(i)-
theta_0))]|[(x(i)<=theta_L)&(gamma*E*J(i)<=sigma*(x(i)-theta_0))],
      block.Derivatives.Data(i) = -sigma*(x(i)-theta_0);
else block.Derivatives.Data(i) = gamma*E*J(i)-sigma*(x(i)-theta_0);
end
end

% block.Derivatives.Data(length(x):)
%endfunction

function Terminate(block)

globalfuzzy_u;
globalfuzzy_final;
clear indicator;
fuzzy_final = fuzzy_u;
%endfunction
```

```
% To run the simulation:
%     Step 1: Load the fuzzy controller ( as "u") to the workspace
%     Step 2: Run 1 of the initializing parameters files
%============================================================

%=====Controller parameters=========
k=[1;1];
Q=[20 0;0 10];

% ==================================
V=0.367;
bc=[0;1];
A=[0 1;-k(1) -k(2)];
%Q=q*eye(size(A));
P=lyap(transpose(A),Q);
```

```
%P=[7 1;1 2];
%Q=-(transpose(A)*P+P*A);
% ===================================

%system order%

n=2;
%=====Fuzzy system f's parameters===
fuzzy_u=readfis('FC_NNS1_3'); %name of the fuzzy controller
globalfuzzy_final; %initialize the final fuzzy system
Mu=length(fuzzy_u.rule); % number of rules. This is needed to display the
correct number of adaptive parameters
AFS_params.gamma=100;
AFS_params.sigma=0.05;
AFS_params.theta_U=2;
AFS_params.theta_L=-2;
AFS_params.theta_0=0;

%===========Structure Learning parameters====%
clear structure_learning_params;
structure_learning_params.mf_threshold = 0.5;
structure_learning_params.error_threshold = 2;
structure_learning_params.a0 = [2 2 2];
structure_learning_params.center_distance_threshold = [0.5 0.5 0.5];
structure_learning_params.max_N_rules = 15;
%-----------
%eB=0.01;
%lamda_w=1;
%zeta_w=0.005;
%w0=0.1;
%w_max=2;
%e1=20;
%=======================================%
%e10=0.00;
%e11=0.00;
%E0=0.002;
%T0=20;
```

```
function
fis_out=generate_rules(fuzzy_input,var_index,mf_index,initial_value)
%=============================================================================
% This function is use to generate all the rules when a new mf is added in
a dimension.
%
% var_index and mf_index indicate the dimension and the index of the added
%  mf.
%
% initial_value is the value that the outputs of the rules will be
% initialized to.
%=============================================================================


%=========================Adding membership functions to output===========

%===Determine the number N_output_mfs of required output membership
functions===
            Num_Input_MFs = getfis(fuzzy_input,'NumInputMFs');
```

```
            N_available_mfs = Num_Input_MFs; % N_available_mfs is the
matrix of number of available mfs for creating new rules
            N_available_mfs(var_index) = 1;

            N_added_output_mfs = prod(N_available_mfs);

%===============================================================
if N_added_output_mfs ~= 0
%===Adding constant membership functions (and initilize them to
initial_value) to output===============
            current_N_rules = getfis(fuzzy_input,'NumRules');
for i=1:N_added_output_mfs,
               mf_name=strcat('mf',num2str(current_N_rules+i));
fuzzy_input=addmf(fuzzy_input,'output',1,mf_name,'constant',initial_value);
end

%========================Adding rules to the fuzzy system==================


%===determine the rulelist=========================================
         Rulelist=[];
         Matrix_out=[];
%===initiate matrix_out which contains
for i=1:getfis(fuzzy_input,'input',1,'NumMFs')
            Matrix_out=[Matrix_out;i];
end

for i=2:getfis(fuzzy_input,'NumInputs')
                Matrix_out=combine_matrix(Matrix_out,N_available_mfs(i));
end

for i=1:N_added_output_mfs
            Rulelist=[Rulelist;Matrix_out(i,:) (current_N_rules+i) 1 1];
end

         mf_index_vector = ones(N_added_output_mfs,1)*mf_index;
         Rulelist(:,var_index) = mf_index_vector;

%===Adding rules==================================================
fuzzy_input=addrule(fuzzy_input,Rulelist);

end

fis_out=fuzzy_input;



function Matrix_out=combine_matrix(Matrix_in,N_mfs)

Matrix_out=[];

for i=1:length(Matrix_in(:,1))
for j=1:N_mfs
        Matrix_out=[Matrix_out;Matrix_in(i,:) j];
end
end
```

```
function [sys,x0,str,ts] = estimator(t,x,u,flag,k,P,bc)
%SFUNTMPL General M-file S-function template
%   With M-file S-functions, you can define you own ordinary differential
%   equations (ODEs), discrete system equations, and/or just about
%   any type of algorithm to be used within a Simulink block diagram.
%
%   The general form of an M-File S-function syntax is:
%       [SYS,X0,STR,TS] = SFUNC(T,X,U,FLAG,P1,...,Pn)
%
%   What is returned by SFUNC at a given point in time, T, depends on the
%   value of the FLAG, the current state vector, X, and the current
%   input vector, U.
%
%   FLAG   RESULT             DESCRIPTION
%   -----  ------             --------------------------------------------
%   0      [SIZES,X0,STR,TS]  Initialization, return system sizes in SYS,
%                             initial state in X0, state ordering strings
%                             in STR, and sample times in TS.
%   1      DX                 Return continuous state derivatives in SYS.
%   2      DS                 Update discrete states SYS = X(n+1)
%   3      Y                  Return outputs in SYS.
%   4      TNEXT              Return next time hit for variable step sample
%                             time in SYS.
%   5                         Reserved for future (root finding).
%   9      []                 Termination, perform any cleanup SYS=[].
%
%
%   The state vectors, X and X0 consists of continuous states followed
%   by discrete states.
%
%   Optional parameters, P1,...,Pn can be provided to the S-function and
%   used during any FLAG operation.
%
%   When SFUNC is called with FLAG = 0, the following information
%   should be returned:
%
%      SYS(1) = Number of continuous states.
%      SYS(2) = Number of discrete states.
%      SYS(3) = Number of outputs.
%      SYS(4) = Number of inputs.
%               Any of the first four elements in SYS can be specified
%               as -1 indicating that they are dynamically sized. The
%               actual length for all other flags will be equal to the
%               length of the input, U.
%      SYS(5) = Reserved for root finding. Must be zero.
%      SYS(6) = Direct feedthrough flag (1=yes, 0=no). The s-function
%               has direct feedthrough if U is used during the FLAG=3
%               call. Setting this to 0 is akin to making a promise that
%               U will not be used during FLAG=3. If you break the promise
%               then unpredictable results will occur.
%      SYS(7) = Number of sample times. This is the number of rows in TS.
%
%
%      X0     = Initial state conditions or [] if no states.
%
%      STR    = State ordering strings which is generally specified as [].
%
%      TS     = An m-by-2 matrix containing the sample time
%                (period, offset) information. Where m = number of sample
```

```
%               times. The ordering of the sample times must be:
%
%               TS = [0      0,      : Continuous sample time.
%                     0      1,      : Continuous, but fixed in minor step
%                                      sample time.
%                     PERIOD OFFSET, : Discrete sample time where
%                                      PERIOD > 0 & OFFSET < PERIOD.
%                     -2     0];     : Variable step discrete sample time
%                                      where FLAG=4 is used to get time of
%                                      next hit.
%
%               There can be more than one sample time providing
%               they are ordered such that they are monotonically
%               increasing. Only the needed sample times should be
%               specified in TS. When specifying than one
%               sample time, you must check for sample hits explicitly by
%               seeing if
%                  abs(round((T-OFFSET)/PERIOD) - (T-OFFSET)/PERIOD)
%               is within a specified tolerance, generally 1e-8. This
%               tolerance is dependent upon your model's sampling times
%               and simulation time.
%
%               You can also specify that the sample time of the S-function
%               is inherited from the driving block. For functions which
%               change during minor steps, this is done by
%               specifying SYS(7) = 1 and TS = [-1 0]. For functions which
%               are held during minor steps, this is done by specifying
%               SYS(7) = 1 and TS = [-1 -1].

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%   $Revision: 1.12 $
%
% The following outlines the general structure of an S-function.
%
switch flag,

%%%%%%%%%%%%%%%%%%
% Initialization %
%%%%%%%%%%%%%%%%%%
case 0,
    [sys,x0,str,ts]=mdlInitializeSizes;

%%%%%%%%%%%%%%%%%%%
% Unhandled flags %
%%%%%%%%%%%%%%%%%%%
case {1,2,4,9}
    sys=[];

%%%%%%%%%%%
% Outputs %
%%%%%%%%%%%
case 3,
    sys=mdlOutputs(t,x,u,k,P,bc);

%%%%%%%%%%%%%%%%%%%%
% Unexpected flags %
%%%%%%%%%%%%%%%%%%%%
otherwise
    error(['Unhandled flag = ',num2str(flag)]);
```

```
end

% end sfuntmpl

%
%==============================================================================
===
% mdlInitializeSizes
% Return the sizes, initial conditions, and sample times for the S-
function.
%==============================================================================
===
%
function [sys,x0,str,ts]=mdlInitializeSizes

%
% call simsizes for a sizes structure, fill it in and convert it to a
% sizes array.
%
% Note that in this example, the values are hard coded.  This is not a
% recommended practice as the characteristics of the block are typically
% defined by the S-function parameters.
%
sizes = simsizes;

sizes.NumContStates  = 0;
sizes.NumDiscStates  = 0;
sizes.NumOutputs     = 3;
sizes.NumInputs      = -1;
sizes.DirFeedthrough = 1;
sizes.NumSampleTimes = 1;   % at least one sample time is needed

sys = simsizes(sizes);

%
% initialize the initial conditions
%
x0  = [];

%
% str is always an empty matrix
%
str = [];

%
% initialize the array of sample times
% block.SampleTimes = [-1 0];
ts  = [-1 0];

% end mdlInitializeSizes

%

%
%==============================================================================
===
% mdlOutputs
% Return the block outputs.
```

```
%===============================================================================
===
%
function sys=mdlOutputs(t,x,u,k,P,bc)

a=transpose(k)*u;
b=transpose(u)*P*bc;
c=transpose(u)*P*u/2;
sys = [a;b;c];

% end mdlOutputs

%
```

```
% PLOTTING THE FIGURES
% output and desired output
figure;
plot(output.time,output.signals.values(:,1),'k:',output.time,output.signals
.values(:,2),'k-');
axis([0 35 -0.01 0.01]);
ylabel('output and desired output');
xlabel('Time(second)');
legend('desired output','actual output');
grid on;

% tracking error
figure;
plot(tracking_error.time,tracking_error.signals.values(:,1),'k-');
axis([0 35 -0.01 0.01]);
ylabel('tracking error');
xlabel('Time(second)');
grid on;

% current
figure;
plot(control_signal(:,1),-1*control_signal(:,2),'k');
axis([0 35 -2 2]);
ylabel('current');
xlabel('Time(second)');
grid on;

% no of rules and switching flags
figure;
subplot(2,1,1);
plot(flags(:,1),flags(:,3),'k');
axis([0 35 0 20]);
%ylabel('Angular Displacement(rad)');
xlabel('Time(second)');
ylabel('Number of rules');
% axis([0 40 -.02 .8]);
% legend('application 1','application 2','application 3');

subplot(2,1,2);
plot(flags(:,1),flags(:,2),'k');
axis([0 35 -1.5 1.5]);
xlabel('Time(second)');
ylabel('Self-structuring flag');
```

```
% plot membership functions
figure;
plotmf(fuzzy_u,'input',1);

figure;
plotmf(fuzzy_final,'input',1);

figure;
plotmf(fuzzy_final,'input',2);

figure;
plotmf(fuzzy_final,'input',3);
```

APPENDIX C

MATLAB CODES FOR FIVE STOREYSTRUCTURE

```
%*************************************************************************
clc                            % FIVE STOREY STRUCTURE
%*************************************************************************
% EQUIPPED WITH A PAIR OF MR DAMPERS IN BETWEEN THE 4TH & 5TH FLOORS
% DUE TO ELCENTRO QUAKE (normalised to 2g) WITH FUZZY LOGIC CONTROLLERS
%                          *******************
% THE FUZZY LOGIC CONTROLLER INPUTS :
%   x4-x5(RELATIVE DISP OF 4TH&5TH FLOORS) +
%   v4-v5 (RELATIVE VELO OF 4TH&5TH FLOORS)
% THE FUZZY LOGIC CONTROLLER OUTPUT :
%   i (CURRENT).
%                          *******************
% THE MR DAMPER CHARACTERISTICS ARE:
alpha2=-488;alpha1=1836;alpha0=64;beta=100;delta11=0.3;delta10=0.58;
kd1=10200;kd2=-3400;cd1=2464;cd2=3858;
%                          *******************
% THE FIVE STOREY STRUCTURE'S CHARACTERISTICS ARE:
f=2.95; % f is the fundamental frequency (Hz)
saay=0.004; % saay is the critical damping
m1=3273;m2=3273;m3=3273;m4=3273;m5=3273; % m in N.
k1=778000;k2=1160000;k3=1160000;k4=1160000;k5=1160000; % k in N/m.
c1=485;c2=485;c3=485;c4=485;c5=485; % c in Ns/m.
%                          *******************
% THE CURRENT(i) IS THE OUTPUT OF THE FUZZY LOGIC CONTROLLER
% THE INPUT TO THE MR DAMPER :  0 < i < imax = 2A
%                          *******************
%                                  PLOT
%                          *******************
%h=plot(x5con,'red');
%hold on
%hh=plot(x5uncon);
%set(h,{'DisplayName'},{'x5con(m)'}')
%set(hh,{'DisplayName'},{'x5uncon(m)'}')
%legend show
%ii=plot(i,'red');
%set(q,{'DisplayName'},{'current(i)'}')
%legend show
%                         **********************
%                          det([k]-(w^2)*[m])=0
%                         **********************
%[m]=diag([m1,m2,m3,m4,m5]);
%[k]=diag([k1,k2,k3,k4,k5]);
%[k]=[k]+diag([k2,k3,k4,k5,0]);
%[k]=[k]+zeros(5,5);
%k(1,2)=-k2;k(2,3)=-k3;k(3,4)=-k4;k(4,5)=-k5;
%k(2,1)=-k2;k(3,2)=-k3;k(4,3)=-k4;k(5,4)=-k5;
%[c]=diag([c1,c2,c3,c4,c5]);
%[c]=[c]+diag([c2,c3,c4,c5,0]);
%[c]=[c]+zeros(5,5);
%c(1,2)=-c2;c(2,3)=-c3;c(3,4)=-c4;c(4,5)=-c5;
%c(2,1)=-c2;c(3,2)=-c3;c(4,3)=-c4;c(5,4)=-c5;
%                         *********************
% display(m)
% display(k)
```

```
% display(c)
%                         ********************
%syms w A2
%A1=[k]-([m]*((w)^2));
%A2=det(A1);
%A3=solve(A2);
%w=A3;
%f=(1/(2*pi))*w
```

```
% LEARNING PARAMETERS FOR THE ADAPTIVE FUZZY SYSTEM

function [fuzzy_output,indicator1] =
structure_learning(z,fuzzy_input,error,structure_learning_params,current_ou
tput)

% This function performs structure learning of the fuzzy system. This
% function can only be used for rectangular-mf fuzzy systems.
%
% error is the output error or tracking error

% current output is the current value of the fuzzy system output

% mf_threshold is a threshold that a new mf is considered if the max mf
% degree in any input dimension is smaller than this value

% error_threshold is a threshold that a new mf is considered if the output
% error (or tracking error) is smaller than this value

% a0 is the matrix specifies the 1/2 the maximum predefined spreads of
% rectangular mfs in each dimension
% mf_degree_threshold (which characterizes the similarity between the mf
center and the input) is the threshold that a mf should be
% replaced by a new one if the mf degree of the input is larger or equal to
this
% value
mf_threshold = structure_learning_params.mf_threshold;
error_threshold = structure_learning_params.error_threshold;
a0 = structure_learning_params.a0;
center_distance_threshold =
structure_learning_params.center_distance_threshold;
max_N_rules = structure_learning_params.max_N_rules;

persistent indicator

if isempty(indicator)
   indicator = 1;
end

%==========initialize the first rule to the first input entered======

% ======================================================================
% ======= Part 3================
if abs(error) >= error_threshold % then a new mf is added or replaced


% Determine the most firing rule
```

```
[most_firing_rule_strength,most_firing_rule_index]=max(current_output.ARR);

% The result of evaluating input values through mfs of the most firing rule
    mf_degree_vector = current_output.IRR(most_firing_rule_index,:); %
mf_degree_vector contains the result of evaluating input
% values through mfs of the most firing rule


% Determine the dimension in which the max mf degree obtains
    [max_mf_degree,var_index] = max(mf_degree_vector);% var_index2 is the
dimension in which max mf degree obtains

% Determine new_N_rules would be reached when adding one more mf.
    Num_Input_MFs = getfis(fuzzy_input,'NumInputMFs');
    new_Num_Input_MFs = Num_Input_MFs;
    new_Num_Input_MFs(var_index) = Num_Input_MFs(var_index)+1;
    new_N_rules = prod(new_Num_Input_MFs);

% Determine if a new mf should be considered based on the similarity
% measure. If center_distance is smaller than center_distance_threshold, a
new rule
% should not be added.
    most_activated_mf_index = 0;
    Rulelist = getfis(fuzzy_input,'Rulelist');
    most_activated_mf_index = Rulelist(most_firing_rule_index,var_index);
    most_activated_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',most_activated_mf_index,'params')
;
    center_distance = abs(z(var_index)-most_activated_mf_params(2));

    similarity_measure = 1;
if center_distance<center_distance_threshold(var_index)
        similarity_measure = 1; % "1" represents "similar"
else
        similarity_measure = 0; % "0" represents "not similar"
end

if (similarity_measure == 0)&&(new_N_rules > max_N_rules) % replace a mf by
a new one

% Determine the mf_to_be_replaced which is the farest mf
        farest_mf_index = 0;
        max_abs_distance = 0;
for i=1:getfis(fuzzy_input,'input',var_index,'nummfs')
            current_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
            distance = current_params(2)-z(var_index);
if abs(distance)>max_abs_distance
                max_abs_distance = abs(distance);
                farest_mf_index = i;
end
end
        mf_to_be_replaced_index = farest_mf_index;

% Determine the left, right mfs
        left_mf_index = 0;
        right_mf_index = 0;
        min_left_distance = -4;
```

```
        min_right_distance = 4;
for i=1:getfis(fuzzy_input,'input',var_index,'nummfs')
            current_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
            distance = current_params(2)-z(var_index);
if (distance<0) && (distance>min_left_distance) && (i ~=
mf_to_be_replaced_index)
                min_left_distance = distance;
                left_mf_index = i;
end
if (distance>0) && (distance<min_right_distance) && (i ~=
mf_to_be_replaced_index)
                min_right_distance = distance;
                right_mf_index = i;
end
end


% Replace the mf_to_be_replaced by a new one
fuzzy_input =
replace_mf_and_rules(fuzzy_input,var_index,a0,left_mf_index,z(var_index),ri
ght_mf_index,mf_to_be_replaced_index,current_output.output);
        indicator =indicator*(-1);
end

if (similarity_measure == 0)&&(new_N_rules <= max_N_rules) % then add a new
mf

% Determine the left, right mfs
        left_mf_index = 0;
        right_mf_index = 0;
        min_left_distance = -4;
        min_right_distance = 4;
for i=1:getfis(fuzzy_input,'input',var_index,'nummfs')
            current_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
            distance = current_params(2)-z(var_index);
if (distance<0) && (distance>min_left_distance)
                min_left_distance = distance;
                left_mf_index = i;
end
if (distance>0) && (distance<min_right_distance)
                min_right_distance = distance;
                right_mf_index = i;
end
end

fuzzy_input =
add_mf_and_rules(fuzzy_input,var_index,a0,left_mf_index,z(var_index),right_
mf_index,current_output.output);
        indicator =indicator*(-1);
end
else
% ====================Part 1===================

if getfis(fuzzy_input,'NumRules')>1
        [IRR_max,rule_index_vector] = max(current_output.IRR);          %
IRR_max is the vector of the max values of inputs through membership
% functions in each dimension
```

```
% rule_index_vector is the vector containing indexes of rules that max
values
% of inputs through mfs achieve in each dimension.
        [min_IRR_max,var_index] = min(IRR_max);         % min_IRR_max is
the min value of IRR_max.
% var_index is the dimension which the min value of IRR_max achieves
        rule_index = rule_index_vector(var_index);      % rule_index is the
index of rule that min value of IRR_max achieves
else
        rule_index = 1;
        [min_IRR_max,var_index] = min(current_output.IRR);
end
    Rulelist = getfis(fuzzy_input,'Rulelist');
    mf_index = Rulelist(rule_index,var_index);      % mf_index indicates
the membership function which the min value archieves


% ====================Part 2===================
if min_IRR_max<mf_threshold % then a new mf is added or replaced to either
sides

% add 1 rectangular mf in var_index dimension. This script can only be
% used for rectangular mfs, it needs modification to be used for
% gaussian membership functions

% Determine new_N_rules would be reached when adding one more mf.
        Num_Input_MFs = getfis(fuzzy_input,'NumInputMFs');
        new_Num_Input_MFs = Num_Input_MFs;
        new_Num_Input_MFs(var_index) = Num_Input_MFs(var_index)+1;
        new_N_rules = prod(new_Num_Input_MFs);

if new_N_rules > max_N_rules % then we need to replace an existing mf by a
new mf

% Determine the farest mf
            farest_mf_index = 0;
            max_abs_distance = 0;
for i=1:getfis(fuzzy_input,'input',var_index,'nummfs')
                current_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
                distance = current_params(2)-z(var_index);
if abs(distance)>=max_abs_distance
                    max_abs_distance = abs(distance);
                    farest_mf_index = i;
end
end
            mf_to_be_replaced_index = farest_mf_index;

% Determine the left, right, excluding the mf_to_be_replaced
            left_mf_index = 0;
            right_mf_index = 0;
            min_left_distance = -4;
            min_right_distance = 4;
            center = 0;
for i=1:getfis(fuzzy_input,'input',var_index,'nummfs')
                current_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
                distance = current_params(2)-z(var_index);
if (distance<0) && (distance>min_left_distance) && (i ~=
mf_to_be_replaced_index)
```

```
                    min_left_distance = distance;
                    left_mf_index = i;
                    left_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
                    center = left_mf_params(3);
end
if (distance>0) && (distance<min_right_distance) && (i ~=
mf_to_be_replaced_index)
                    min_right_distance = distance;
                    right_mf_index = i;
                    right_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
                    center = right_mf_params(1);
end
end

fuzzy_input =
replace_mf_and_rules(fuzzy_input,var_index,a0,left_mf_index,center,right_mf
_index,mf_to_be_replaced_index,current_output.output);

% Set indicator = 1 or -1 if this case occurs
            indicator = indicator*(-1);


else%add a new mf and add rules

% Determine the left, right mfs
            left_mf_index = 0;
            right_mf_index = 0;
            min_left_distance = -4;
            min_right_distance = 4;
for i=1:getfis(fuzzy_input,'input',var_index,'nummfs')
                current_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
                distance = current_params(2)-z(var_index);
if (distance<0) && (distance>min_left_distance)
                    min_left_distance = distance;
                    left_mf_index = i;
                    left_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
                    center = left_mf_params(3);
end
if (distance>0) && (distance<min_right_distance)
                    min_right_distance = distance;
                    right_mf_index = i;
                    right_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
                    center = right_mf_params(1);
end
end

fuzzy_input =
add_mf_and_rules(fuzzy_input,var_index,a0,left_mf_index,z(var_index),right_
mf_index,current_output.output);
            indicator =indicator*-1;
end

% Recalculate the output after the fuzzy system changes
% [output, IRR, ORR, ARR]= evalfis(z,fuzzy_input);
```

```
end
end


fuzzy_output = fuzzy_input;
indicator1 = indicator;

%===========================================================================
% GENERATING RULES FOR THE FUZZY SYSTEM

functionfuzzy_output =
replace_mf_and_rules(fuzzy_input,var_index,a0,left_mf_index,center,right_mf
_index,mf_to_be_replaced_index,initial_value)

% Modify the mf neibouring to the farest mf (it is either left or right
neibouring mf)

% Determine the neibouring mf of the farest mf
    farest_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',mf_to_be_replaced_index,'params')
;
    left_farest_mf_index = 0;
    right_farest_mf_index = 0;
    min_left_farest_distance = -4;
    min_right_farest_distance = 4;
for i=1:getfis(fuzzy_input,'input',var_index,'nummfs')
        current_params =
getfis(fuzzy_input,'input',var_index,'mf',i,'params');
        distance = current_params(2)-farest_mf_params(2);
if (distance<0) && (distance>min_left_farest_distance)
            min_left_farest_distance = distance;
            left_farest_mf_index = i;
end
if (distance>0) && (distance<min_right_farest_distance)
            min_right_farest_distance = distance;
            right_farest_mf_index = i;
end
end

% Modify the left param if the neibouring mf of the farest mf is on the
left
if left_farest_mf_index ~= 0
        left_farest_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',left_farest_mf_index,'params');
        left_farest_mf_params(3) = left_farest_mf_params(2)+a0(var_index);
fuzzy_input =
setfis(fuzzy_input,'input',var_index,'mf',left_farest_mf_index,'params',lef
t_farest_mf_params);
end

% Modify the right param if the neibouring mf of the farest mf is on the
right
if right_farest_mf_index ~= 0
        right_farest_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',right_farest_mf_index,'params');
        right_farest_mf_params(1) = right_farest_mf_params(2)-
a0(var_index);
fuzzy_input =
setfis(fuzzy_input,'input',var_index,'mf',right_farest_mf_index,'params',ri
ght_farest_mf_params);
```

```
end

% modify the neibourhood mfs of the new added mf if there exist ones
if left_mf_index ~= 0
    left_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',left_mf_index,'params');
    left_mf_params(3) = center;
fuzzy_input =
setfis(fuzzy_input,'input',var_index,'mf',left_mf_index,'params',left_mf_pa
rams);
end

if right_mf_index ~= 0;
    right_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',right_mf_index,'params');
    right_mf_params(1) = center;
fuzzy_input =
setfis(fuzzy_input,'input',var_index,'mf',right_mf_index,'params',right_mf_
params);
end

% Determine the params of the new mf
if left_mf_index == 0
    new_mf_params(1) = center-a0(var_index);
else
    new_mf_params(1)= left_mf_params(2);
end
    new_mf_params(2) = center;
if right_mf_index == 0
    new_mf_params(3) = center+a0(var_index);
else
    new_mf_params(3)= right_mf_params(2);
end

% Replace the farest mf by a new mf and initialize all the related rules to
the current output
fuzzy_input =
setfis(fuzzy_input,'input',var_index,'mf',mf_to_be_replaced_index,'params',
new_mf_params);

% Initialize all the related rules to the current output
Rulelist = getfis(fuzzy_input,'Rulelist');
for i=1:getfis(fuzzy_input,'NumRules')
if Rulelist(i,var_index)==mf_to_be_replaced_index
fuzzy_input = setfis(fuzzy_input,'output',1,'mf',i,'params',initial_value);
end
end



fuzzy_output = fuzzy_input;

functionfuzzy_output =
add_mf_and_rules(fuzzy_input,var_index,a0,left_mf_index,center,right_mf_ind
ex,initial_value)


% modify the neibourhood mfs if there exist ones
if left_mf_index ~= 0
```

```
    left_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',left_mf_index,'params');
    left_mf_params(3) = center;
fuzzy_input =
setfis(fuzzy_input,'input',var_index,'mf',left_mf_index,'params',left_mf_pa
rams);
end

if right_mf_index ~= 0;
    right_mf_params =
getfis(fuzzy_input,'input',var_index,'mf',right_mf_index,'params');
    right_mf_params(1) = center;
fuzzy_input =
setfis(fuzzy_input,'input',var_index,'mf',right_mf_index,'params',right_mf_
params);
end

% Determine the params of the new mf
if left_mf_index == 0
    new_mf_params(1) = center-a0(var_index);
else
    new_mf_params(1)= left_mf_params(2);
end
    new_mf_params(2) = center;
if right_mf_index == 0
    new_mf_params(3) = center+a0(var_index);
else
    new_mf_params(3)= right_mf_params(2);
end

% Add a new mf
added_mf_index = getfis(fuzzy_input,'input',var_index,'Nummfs')+1; % the
index indicates the new mf
mf_name = strcat('mf',num2str(added_mf_index));
fuzzy_input =
addmf(fuzzy_input,'input',var_index,mf_name,'trimf',new_mf_params);

% Add rules using generate_rules function
fuzzy_input=generate_rules(fuzzy_input,var_index,added_mf_index,initial_val
ue);

fuzzy_output = fuzzy_input;
```

```
% GENERATING THE SELF ORGANIZING ADAPTIVE FUZZY LOGIC CONTROLLER

function SOAFS(block)

setup(block);

function setup(block)

    block.NumDialogPrms     = 3;

% get the initial number of adaptive parameters = number of rules
fuzzy_u = block.DialogPrm(1).Data;
% AFS_params = block.DialogPrm(2).Data;
     structure_learning_params = block.DialogPrm(3).Data;
% no_of_rules = getfis(fuzzy_u,'NumRules');
```

```
    block.NumInputPorts  = 2;
    block.NumOutputPorts = 3;

    block.SetPreCompInpPortInfoToDynamic;
    block.SetPreCompOutPortInfoToDynamic;

    block.InputPort(1).Complexity   = 'Real';
    block.InputPort(1).DataTypeId   = 0;
    block.InputPort(1).SamplingMode = 'Sample';
    block.InputPort(1).Dimensions   = 1;

    block.InputPort(2).Complexity   = 'Real';
    block.InputPort(2).DataTypeId   = 0;
    block.InputPort(2).SamplingMode = 'Sample';
    block.InputPort(2).Dimensions   = getfis(fuzzy_u,'NumInputs');

    block.OutputPort(1).Complexity   = 'Real';
    block.OutputPort(1).DataTypeId   = 0;
    block.OutputPort(1).SamplingMode = 'Sample';
    block.OutputPort(1).Dimensions   = 1;

    block.OutputPort(2).Complexity   = 'Real';
    block.OutputPort(2).DataTypeId   = 0;
    block.OutputPort(2).SamplingMode = 'Sample';
    block.OutputPort(2).Dimensions   =
structure_learning_params.max_N_rules;

    block.OutputPort(3).Complexity   = 'Real';
    block.OutputPort(3).DataTypeId   = 0;
    block.OutputPort(3).SamplingMode = 'Sample';
    block.OutputPort(3).Dimensions   = 2;

    block.SampleTimes = [0 0];

    block.RegBlockMethod('Start', @Start);
    block.RegBlockMethod('Outputs', @Outputs);
    block.RegBlockMethod('Derivatives', @Derivatives);
    block.RegBlockMethod('Terminate', @Terminate);

% set the block' number of continuous states
    block.NumContStates=structure_learning_params.max_N_rules;

%end setup function

function Start(block)

globalfuzzy_u;
fuzzy_u= block.DialogPrm(1).Data;
  no_of_rules = getfis(fuzzy_u,'NumRules');

% initialize the continuous state vector
 output_params= getfis(fuzzy_u,'OutMFParams');

 block.ContStates.Data(1:length(output_params)) = output_params(:,1);

%end function
```

```
function Outputs(block)

globalfuzzy_u
%fuzzy_u = block.DialogPrm(1).Data;
no_of_rules = getfis(fuzzy_u,'NumRules');

X=block.InputPort(2).data;

inRange = getfis(fuzzy_u,'inRange');
X=saturation_ppa(X,inRange); % see function saturation_ppa in "my m files"
for instructions

x = block.ContStates.Data(1:no_of_rules);


fuzzy_u=setfis(fuzzy_u,'OutMFParams',x);

[current_output.output, current_output.IRR, current_output.ORR,
current_output.ARR]= evalfis(X,fuzzy_u);


block.OutputPort(1).Data = current_output.output;
block.OutputPort(2).Data(1:no_of_rules) = x;

[fuzzy_u,indicator1] =
structure_learning(X,fuzzy_u,block.InputPort(1).data,block.DialogPrm(3).Dat
a,current_output);

block.OutputPort(3).Data(1) = indicator1;
block.OutputPort(3).Data(2) = getfis(fuzzy_u,'NumRules');
%endfunction

function Derivatives(block)

globalfuzzy_u;
%fuzzy_u = block.DialogPrm(1).Data;
E=block.InputPort(1).data; % the first input is the error(adaptive signal);

X=block.InputPort(2).data; % the other inputs are the state vector of the
system
inRange = getfis(fuzzy_u,'inRange');
X=saturation_ppa(X,inRange); % see function saturation_ppa in "my m files"
for instructions

%fuzzy_u = block.DialogPrm(1).Data;
AFS_params = block.DialogPrm(2).Data;
gamma  = AFS_params.gamma;
sigma  = AFS_params.sigma;
theta_U = AFS_params.theta_U;
theta_L = AFS_params.theta_L;
theta_0 = AFS_params.theta_0;

% structure_learning_params = block.DialogPrm(3).Data;
% fuzzy_u = structure_learning(X,fuzzy_u,E,block.DialogPrm(3).Data);


x= getfis(fuzzy_u,'OutMFParams');
```

```
%outRange = [theta_L theta_U];
%x = saturation_ppa2(x,outRange);

block.ContStates.Data(1:length(x(:,1))) = x(:,1);



[a,b,c,d]=evalfis(X,fuzzy_u);

if sum(d)==0,
    J=zeros(length(d),1);
else
    J = d/sum(d);
end


for i=1:length(x(:,1))
if [(x(i)>=theta_U)&(gamma*E*J(i)>=sigma*(x(i)-
theta_0))]|[(x(i)<=theta_L)&(gamma*E*J(i)<=sigma*(x(i)-theta_0))],
      block.Derivatives.Data(i) = -sigma*(x(i)-theta_0);
else block.Derivatives.Data(i) = gamma*E*J(i)-sigma*(x(i)-theta_0);
end
end

% block.Derivatives.Data(length(x):)
%endfunction

function Terminate(block)

globalfuzzy_u;
globalfuzzy_final;
clear indicator;
fuzzy_final = fuzzy_u;
%endfunction
```

```
% GENERATING THE LEARNING PARAMETERS FOR THE ADAPTIVE FUZZY LOGIC
CONTROLLER


% To run the simulation:
%     Step 1: Load the fuzzy controller ( as "u") to the workspace
%     Step 2: Run 1 of the initializing parameters files
%============================================================

%=====Controller parameters=========
k=[1;1];
Q=[20 0;0 10];

% ==================================
V=0.367;
bc=[0;1];
A=[0 1;-k(1) -k(2)];
%Q=q*eye(size(A));
P=lyap(transpose(A),Q);
%P=[7 1;1 2];
%Q=-(transpose(A)*P+P*A);
```

```
% ===================================

%system order%

n=2;
%=====Fuzzy system f's parameters===
fuzzy_u=readfis('FC_NNS1_3'); %name of the fuzzy controller
globalfuzzy_final; %initialize the final fuzzy system
Mu=length(fuzzy_u.rule); % number of rules. This is needed to display the
correct number of adaptive parameters
AFS_params.gamma=100;
AFS_params.sigma=0.05;
AFS_params.theta_U=2;
AFS_params.theta_L=0;
AFS_params.theta_0=0;

%===========Structure Learning parameters====%
clear structure_learning_params;
structure_learning_params.mf_threshold = 0.5;
structure_learning_params.error_threshold =2;
structure_learning_params.a0 = [1 1 1];
structure_learning_params.center_distance_threshold = [0.5 0.5 0.5];
structure_learning_params.max_N_rules = 15;
%-----------
%eB=0.01;
%lamda_w=1;
%zeta_w=0.005;
%w0=0.1;
%w_max=2;
%e1=20;

%=======================================%
%e10=0.00;
%e11=0.00;
%E0=0.002;
%T0=20;
```

```
% GENERATING RULES FOR THE FUZZY SYSTEM

function
fis_out=generate_rules(fuzzy_input,var_index,mf_index,initial_value)
%==========================================================================
% This function is use to generate all the rules when a new mf is added in
a dimension.
%
% var_index and mf_index indicate the dimension and the index of the added
%  mf.
%
% initial_value is the value that the outputs of the rules will be
% initialized to.
%==========================================================================


%=========================Adding membership functions to output===========

%===Determine the number N_output_mfs of required output membership
functions===
            Num_Input_MFs = getfis(fuzzy_input,'NumInputMFs');
```

```
            N_available_mfs = Num_Input_MFs; % N_available_mfs is the
matrix of number of available mfs for creating new rules
            N_available_mfs(var_index) = 1;

            N_added_output_mfs = prod(N_available_mfs);

%===============================================================
if N_added_output_mfs ~= 0
%===Adding constant membership functions (and initilize them to
initial_value) to output===
            current_N_rules = getfis(fuzzy_input,'NumRules');
for i=1:N_added_output_mfs,
               mf_name=strcat('mf',num2str(current_N_rules+i));
fuzzy_input=addmf(fuzzy_input,'output',1,mf_name,'constant',initial_value);
end

%========================Adding rules to the fuzzy system==================


%===determine the rulelist==========================================
         Rulelist=[];
         Matrix_out=[];
%===initiate matrix_out which contains
for i=1:getfis(fuzzy_input,'input',1,'NumMFs')
            Matrix_out=[Matrix_out;i];
end

for i=2:getfis(fuzzy_input,'NumInputs')
                Matrix_out=combine_matrix(Matrix_out,N_available_mfs(i));
end

for i=1:N_added_output_mfs
            Rulelist=[Rulelist;Matrix_out(i,:) (current_N_rules+i) 1 1];
end

         mf_index_vector = ones(N_added_output_mfs,1)*mf_index;
         Rulelist(:,var_index) = mf_index_vector;

%===Adding rules====================================================
fuzzy_input=addrule(fuzzy_input,Rulelist);

end

fis_out=fuzzy_input;




function Matrix_out=combine_matrix(Matrix_in,N_mfs)

Matrix_out=[];

for i=1:length(Matrix_in(:,1))
for j=1:N_mfs
        Matrix_out=[Matrix_out;Matrix_in(i,:) j];
end
end
```

```
% GENERATING THE ESTIMATOR FUNCTION FOR THE SELF-ORGANISING FLAG


function [sys,x0,str,ts] = estimator(t,x,u,flag,k,P,bc)
%SFUNTMPL General M-file S-function template
%   With M-file S-functions, you can define you own ordinary differential
%   equations (ODEs), discrete system equations, and/or just about
%   any type of algorithm to be used within a Simulink block diagram.
%
%   The general form of an M-File S-function syntax is:
%       [SYS,X0,STR,TS] = SFUNC(T,X,U,FLAG,P1,...,Pn)
%
%   What is returned by SFUNC at a given point in time, T, depends on the
%   value of the FLAG, the current state vector, X, and the current
%   input vector, U.
%
%   FLAG   RESULT             DESCRIPTION
%   -----  ------             --------------------------------------------
%   0      [SIZES,X0,STR,TS]  Initialization, return system sizes in SYS,
%                             initial state in X0, state ordering strings
%                             in STR, and sample times in TS.
%   1      DX                 Return continuous state derivatives in SYS.
%   2      DS                 Update discrete states SYS = X(n+1)
%   3      Y                  Return outputs in SYS.
%   4      TNEXT              Return next time hit for variable step sample
%                             time in SYS.
%   5                         Reserved for future (root finding).
%   9      []                 Termination, perform any cleanup SYS=[].
%
%
%   The state vectors, X and X0 consists of continuous states followed
%   by discrete states.
%
%   Optional parameters, P1,...,Pn can be provided to the S-function and
%   used during any FLAG operation.
%
%   When SFUNC is called with FLAG = 0, the following information
%   should be returned:
%
%      SYS(1) = Number of continuous states.
%      SYS(2) = Number of discrete states.
%      SYS(3) = Number of outputs.
%      SYS(4) = Number of inputs.
%               Any of the first four elements in SYS can be specified
%               as -1 indicating that they are dynamically sized. The
%               actual length for all other flags will be equal to the
%               length of the input, U.
%      SYS(5) = Reserved for root finding. Must be zero.
%      SYS(6) = Direct feedthrough flag (1=yes, 0=no). The s-function
%               has direct feedthrough if U is used during the FLAG=3
%               call. Setting this to 0 is akin to making a promise that
%               U will not be used during FLAG=3. If you break the promise
%               then unpredictable results will occur.
%      SYS(7) = Number of sample times. This is the number of rows in TS.
%
%
%      X0     = Initial state conditions or [] if no states.
%
```

```
%       STR     = State ordering strings which is generally specified as [].
%
%       TS      = An m-by-2 matrix containing the sample time
%                 (period, offset) information. Where m = number of sample
%                 times. The ordering of the sample times must be:
%
%                 TS = [0      0,      : Continuous sample time.
%                       0      1,      : Continuous, but fixed in minor step
%                                        sample time.
%                       PERIOD OFFSET, : Discrete sample time where
%                                        PERIOD > 0 & OFFSET < PERIOD.
%                       -2     0];     : Variable step discrete sample time
%                                        where FLAG=4 is used to get time of
%                                        next hit.
%
%                 There can be more than one sample time providing
%                 they are ordered such that they are monotonically
%                 increasing. Only the needed sample times should be
%                 specified in TS. When specifying than one
%                 sample time, you must check for sample hits explicitly by
%                 seeing if
%                    abs(round((T-OFFSET)/PERIOD) - (T-OFFSET)/PERIOD)
%                 is within a specified tolerance, generally 1e-8. This
%                 tolerance is dependent upon your model's sampling times
%                 and simulation time.
%
%                 You can also specify that the sample time of the S-function
%                 is inherited from the driving block. For functions which
%                 change during minor steps, this is done by
%                 specifying SYS(7) = 1 and TS = [-1 0]. For functions which
%                 are held during minor steps, this is done by specifying
%                 SYS(7) = 1 and TS = [-1 -1].

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%   $Revision: 1.12 $
%
% The following outlines the general structure of an S-function.
%
switch flag,

%%%%%%%%%%%%%%%%%%
% Initialization %
%%%%%%%%%%%%%%%%%%
case 0,
    [sys,x0,str,ts]=mdlInitializeSizes;

%%%%%%%%%%%%%%%%%%%
% Unhandled flags %
%%%%%%%%%%%%%%%%%%%
case {1,2,4,9}
    sys=[];

%%%%%%%%%%%
% Outputs %
%%%%%%%%%%%
case 3,
    sys=mdlOutputs(t,x,u,k,P,bc);

%%%%%%%%%%%%%%%%%%%%
% Unexpected flags %
```

```
%%%%%%%%%%%%%%%%%%%%
otherwise
    error(['Unhandled flag = ',num2str(flag)]);

end

% end sfuntmpl

%
%=============================================================================
===
% mdlInitializeSizes
% Return the sizes, initial conditions, and sample times for the S-
function.
%=============================================================================
===
%
function [sys,x0,str,ts]=mdlInitializeSizes

%
% call simsizes for a sizes structure, fill it in and convert it to a
% sizes array.
%
% Note that in this example, the values are hard coded.  This is not a
% recommended practice as the characteristics of the block are typically
% defined by the S-function parameters.
%
sizes = simsizes;

sizes.NumContStates  = 0;
sizes.NumDiscStates  = 0;
sizes.NumOutputs     = 3;
sizes.NumInputs      = -1;
sizes.DirFeedthrough = 1;
sizes.NumSampleTimes = 1;   % at least one sample time is needed

sys = simsizes(sizes);

%
% initialize the initial conditions
%
x0  = [];

%
% str is always an empty matrix
%
str = [];

%
% initialize the array of sample times
% block.SampleTimes = [-1 0];
ts  = [-1 0];

% end mdlInitializeSizes

%

%
```

```
%===========================================================================
===
% mdlOutputs
% Return the block outputs.
%===========================================================================
===
%
function sys=mdlOutputs(t,x,u,k,P,bc)

a=transpose(k)*u;
b=transpose(u)*P*bc;
c=transpose(u)*P*u/2;
sys = [a;b;c];

% end mdlOutputs

%
```

```
% PLOTTING THE FIGURES
% output and desired output
figure;
plot(output.time,output.signals.values(:,1),'k:',output.time,output.signals
.values(:,2),'k-');
axis([0 50 -0.01 0.01]);
ylabel('output and desired output');
xlabel('Time(second)');
legend('desired output','actual output');
grid on;

% tracking error
figure;
plot(tracking_error.time,tracking_error.signals.values(:,1),'k-');
axis([0 50 -0.01 0.01]);
ylabel('tracking error');
xlabel('Time(second)');
grid on;

% current
figure;
plot(control_signal(:,1),control_signal(:,2),'k');
axis([0 50 -0.5 2.5]);
ylabel('current');
xlabel('Time(second)');
grid on;

% no of rules and switching flags
figure;
subplot(2,1,1);
plot(flags(:,1),flags(:,3),'k');
axis([0 50 0 20]);
%ylabel('Angular Displacement(rad)');
xlabel('Time(second)');
ylabel('Number of rules');
% axis([0 40 -.02 .8]);
% legend('application 1','application 2','application 3');

subplot(2,1,2);
plot(flags(:,1),flags(:,2),'k');
```

```
axis([0 50 -1.5 1.5]);
xlabel('Time(second)');
ylabel('Self-structuring flag');


% plot membership functions
figure;
plotmf(fuzzy_u,'input',1);

figure;
plotmf(fuzzy_final,'input',1);

figure;
plotmf(fuzzy_final,'input',2);

figure;
plotmf(fuzzy_final,'input',3);
```

APPENDIX D

7.5. Fuzzy logic

7.5.1. Fuzzy sets

Fuzzy set is the first concept to be introduced in fuzzy logic. It is a set with no clear boundary. It takes into account elements with partial degree of memberships.

Classical sets are the second concept to be introduced in fuzzy logic. A classical set is a classification which includes or excludes any elements provided. The days of the week are a good example which includes Monday, Thursday, and Saturday. It obviously does not include butter, biscuit, and jam etc.

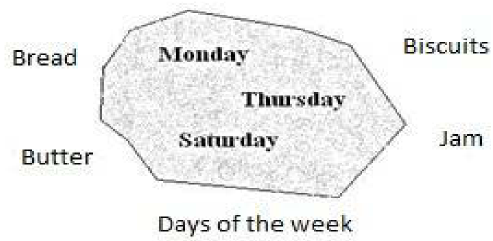


Figure 1. Days of the week

This set is called a classical set as it dates back to many years ago. Aristotle established the law of the Excluded Middle. According to this law, *X* must either be in set *A* or in set *not-A*. A better definition could be like this:

Of any subject, one thing must be either asserted or denied.

Another example; "Of any subject (for example Saturday), one thing (being a day of the week) must be either asserted or denied (I assert that Saturday is a day of the week)." Based on this law, the two classifications *A* and *not-A*, should include the whole universe. Everything is either in one group or the other. There is no classification that belongs to both groups.

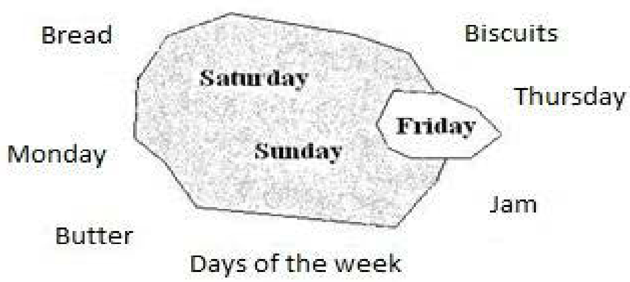


Figure 2. Days of the weekend

Considering the days of the weekend, as shown in the figure above, it is obvious that Saturday and Sunday belong in the weekend days but not Friday. Friday can be partially a weekend day but not fully. Therefore it is categorised as belonging partly to the group of the weekend days, in contrast to the definition of classical sets.

As observed in the above paragraph, a certain classification is not taken into account; even the dictionary is not precise when defining the weekend days as "the duration between Friday night and Saturday to Monday morning". Therefore, a new classification is defined, a classification when sharp yes-no logic is not acceptable in which fuzzy reasoning defines an in between classification of the previous classifications. And so the basic foundations of fuzzy logic have been introduced.

In fuzzy logic, the truth of any statement is considered a matter of degree.

Fuzzy logic introduces the boundary between clear Boolean logic. It discusses the bounds between specific Boolean logic where it introduces boundaries in between, where answers are not quite true or not quite false, but somewhat in between like *0.153* and *0.91*. For example, the set of days for the weekend;

Q: Is Sunday considered a weekend day?

A: 1 (yes, or true)

Q: Is Wednesday considered a weekend day?

A: 0 (no, or false)

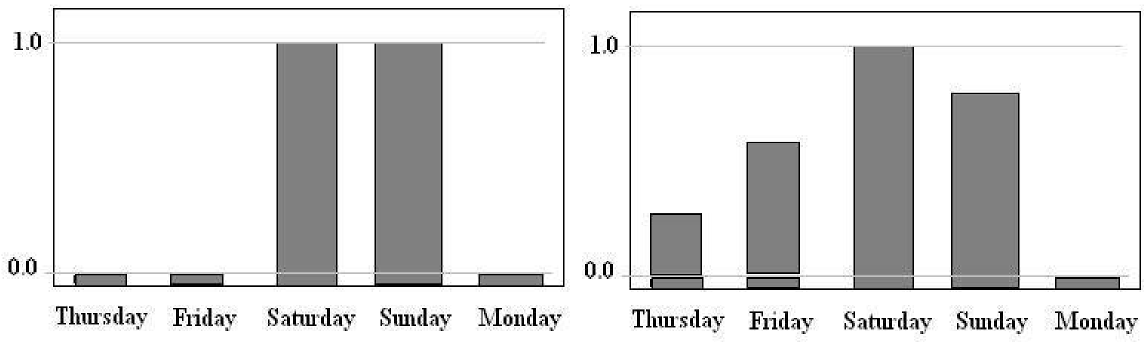
Q: Is Monday considered a weekend day?

A: 0.8 (for the most part yes, but not entirely)

Q: Is Sunday considered a weekend day?

A: 0.95 (yes, but not quite as much as Saturday).

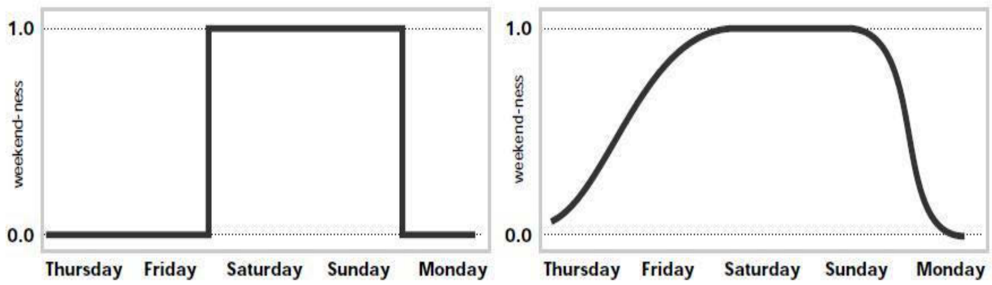
The chart below demonstrates the "weekend-ness" for the set of days considered as the weekend. The chart on the left demonstrates absolute values *(0,1)* where the set of days are either *0* or *1* in contrast to the chart on the right which explains the in between values for "weekend-ness". Therefore, some days of the week are more or less assumed to be considered as the weekend.



(a) (b)

Figure 3. a) Days of the weekend two-valued membership, b) Days of the weekend multi valued membership

If X was a set of something in particular and A was a set, for X to be a member of set A, it could be absolutely a member of set A or not all a member of set A. But since fuzzy reasoning justifies it, X could be any of the thousand in between values. Two-valued logic was first proposed by Aristotle since he first proposed a boundary in between Boolean logic to also be held accountable. As shown in figure 4, on the left chart, there is Boolean logic of the "weekend-ness" and on the right chart, there is the fuzzy in between values for "weekend-ness" for the set of days of a week.



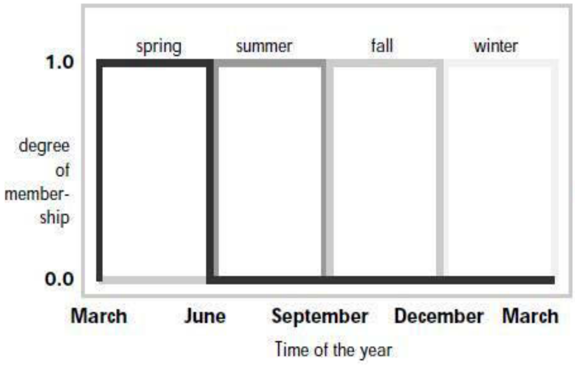
(a) (b)

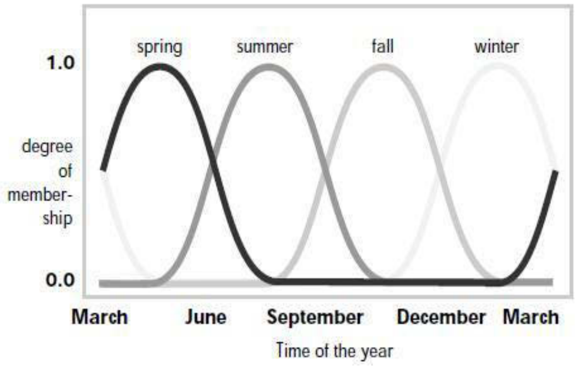
Figure 4. a) Days of the weekend two-valued membership, b) Days of the weekend multi-valued membership

When the plot is made continuous as in figure 4(b), the membership degree of each set becomes a discontinuous value from *0* to *1*. Take the example of "weekend-ness". Thursday, Friday and Monday have a value varying between *0* and *1*, in contrast to Saturday and Sunday which are absolute values of *1*. In other words, Thursday, Friday and Monday have a partial membership in the fuzzy set of "weekend-ness". Therefore, a particular method is introduced which takes into account the discontinuous values between Boolean logics.

The curve that maps the input space (day of the week) to the output space (weekend-ness) is known as the membership function.

Another good example for fuzzy set is the seasons. Seasons vary from the northern hemisphere to the southern hemisphere. Therefore, there is not an absolute rigid method for the duration of each season. Therefore, there needs to be a smooth function that varies for different methods as the seasons change from the northern hemisphere to the southern hemisphere. Figure 5 shows two different membership functions which map different seasons to different months.





(a) (b)

Figure 5. a) Rectangular membership functions, b) Gaussian membership functions for seasons of the year

7.5.2. Membership functions

A *membership function* (MF) is a curve that maps the input to a membership value ranging between *0* and *1*, known as the *universe of discourse*.

A common example of fuzzy sets is the set of tall people. The universe of discourse consists of all heights, from *3* to *9* feet. For different tall to short heights, different universes of discourses are matched. It can be assumed that all heights greater than eight feet are considered "*tall*" and all heights smaller than eight feet to be considered "*short*", but these categorisations are absurd as it is unreasonable to assign one person "*short*" and another person "*tall*" as there are differences in height by the width of a hair. Therefore, there must be in between sets where someone can be to a percentage *short* and to a percentage *tall*.

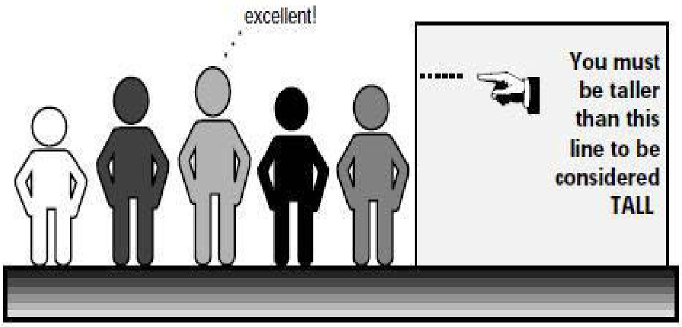


Figure 6. Membership function for different heights

Therefore, the classification discussed so far is unacceptable. Similar to the figure for the set of days assigned to be weekend, this degree of membership figure ranges from *0* to *1*. It defines the transition between *tall* and *not-tall* with a smooth curve in contrast to the previous definition which had an absolute curve for either *tall* or *not-tall* and nothing defined for the in between.

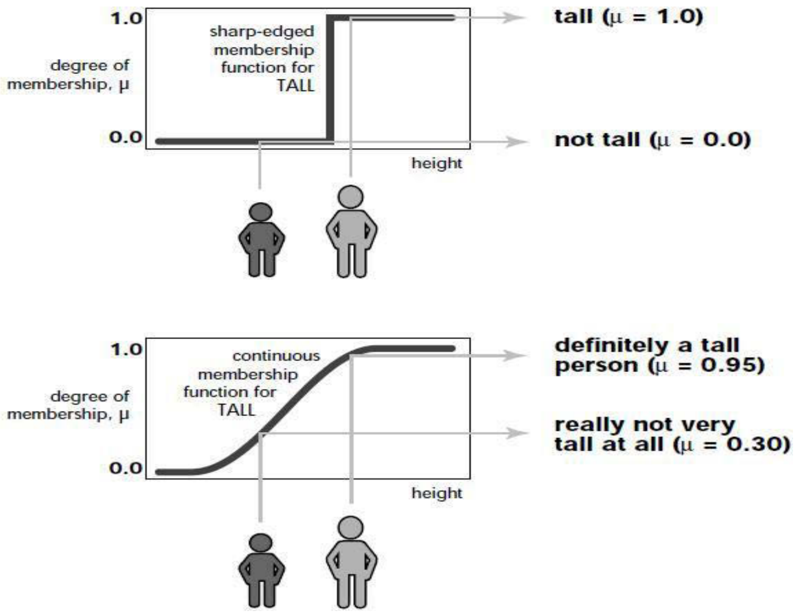


Figure 7. Comparing different membership functions for different heights

Subjective classification is also defined in fuzzy sets. It should be defined whether the term "*tall*" refers to a ten year old child or an adult.

7.5.2.1. Membership functions in the fuzzy logic toolbox

The membership function only varies from *0* to *1*. It can be defined as a smooth curve or a rectangular shaped figure depending on how the case needs to be categorised.

An assumed classical set is in the form below:

$$A = \{x|x > 6\}. \quad (7)$$

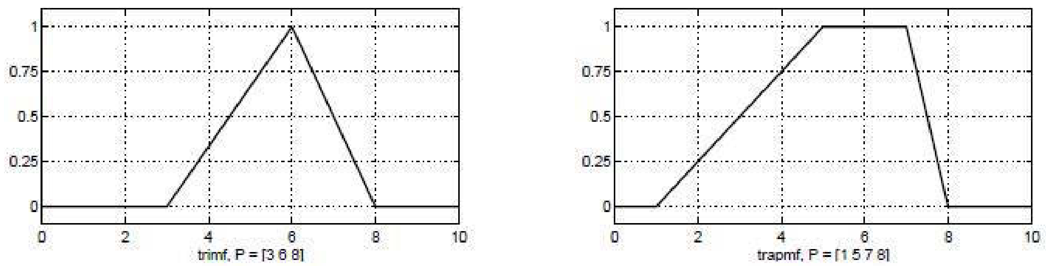
The extended form of a classical set is a fuzzy set. The fuzzy set A is X is shown in the below form:

$$A = \{x, \mu_A(x) \; |x \epsilon X\}; \quad (8)$$

where $\mu_{A(x)}$ is the membership function of x in A. The membership function assigns each element of X to a value between *0* and *1*.

There are a number of built-in membership functions in the fuzzy logic toolbox in MATLAB. These functions are: linear functions, the Sigmoid curves, Gaussian distribution function and quadratic and cubic polynomial curves.

The simple forms of membership functions consist of a series of straight lines. The *triangular* and *trapezoidal* membership functions are good examples, as shown in figure 8. The *trapezoidal* membership function which is a truncated form of triangular membership functions.

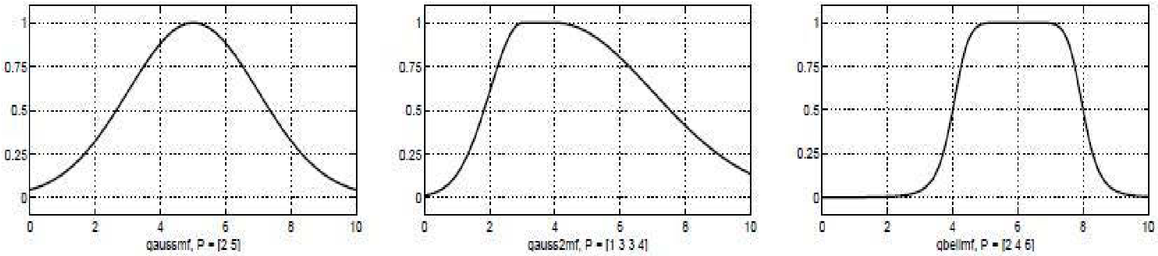


(a) (b)

Figure 8. a) Triangular membership function, b) Trapezoidal membership function

From the *Gaussian* distribution curve, two membership functions can be derived which are *gaussmf* and *gauss2mf*.

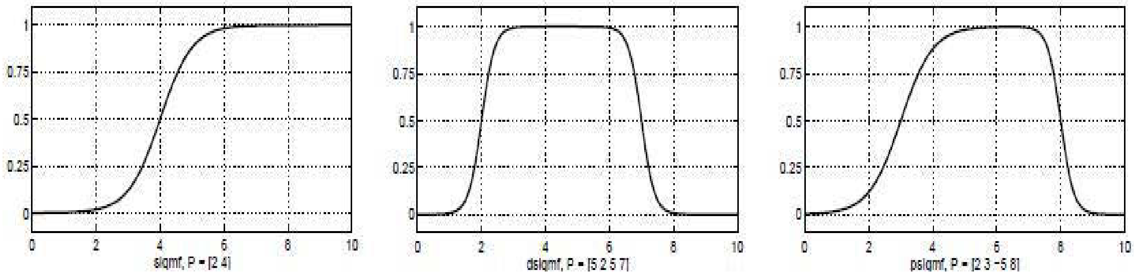
The *generalized bell* membership function is defined by one more parameter than the Gaussian membership function as it has three parameters when defined. Gaussian and bell membership functions owe their popularity to their smooth and concise characteristics.



(a) (b) (c)

Figure 9. a) gaussmf , b) gauss2mf , c) gbellmf

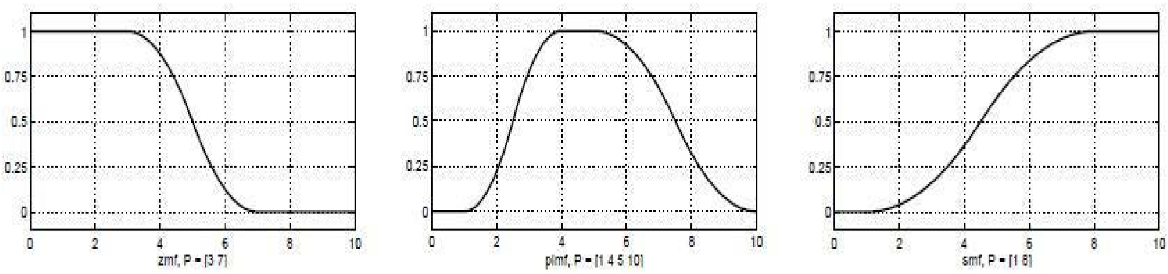
But despite their smoothness, they are not capable of defining asymmetric membership functions. These kinds of membership functions can be specified using two *sigmoidal* functions. In addition to the sigmoidal membership functions, the difference and product of the sigmoidal membership functions known as *dsigmf* and *psigmf*, can also be used for asymmetric functions.



(a) (b) (c)

Figure 10. a) sigmf, b) dsigmf, c) psigmf

Polynomial shaped membership functions are *Z, S*, and *Pi curves*, as their shape resemble these characters. The *Z* membership function is an asymmetric curve which opens to the left in contrast to the *S* membership function which opens to the right and *Pi* starts and ends with zero with a maximum range in the middle.



(a) (b) (c)

Figure 11. a) Z, b) Pi, c) S

The selection of membership functions in the fuzzy logic toolbox is very wide. In addition, this toolbox provides the user the advantage of creating its own arbitrary membership functions. The simplest way would be using the simplest membership functions; the triangle and trapezoid functions, as using unusual or complicated membership functions are not appropriate for simple fuzzy inference systems. More details are presented further in this chapter.

7.5.2.2. Membership functions in summary

- Fuzzy sets take into account ambiguous values and map them to some value in between *0* (absolute false) and *1* (absolute true), in which partial memberships are introduced (Friday is partly a weekend and Mary is to some extent short).
- Membership values map an input value input value (universe of discourse) to a fuzzy set using appropriate membership functions defined by user.

7.5.3. Logical operations

The term *fuzzy* in fuzzy logic has been discussed. The reasoning behind the term "logic" is discussed in this section. Fuzzy logical reasoning is a subset of Boolean logic where fuzzy values can be mapped to the extreme values of *1* (absolutely true) and *0* (absolutely false). The Boolean logic concept is shown in the table below:

A	B	A and B
0	0	0
0	1	0
1	0	0
1	1	1

AND

A	B	A or B
0	0	0
0	1	1
1	0	1
1	1	1

OR

A	not A
0	1
1	0

NOT

Figure 12. Boolean logic

As mentioned above, in fuzzy logic the truth of an input values is mapped to a degree between *0* and *1*. Therefore, a function needs to be defined to perform the *AND* operator for *AANDB*. The *min (A, B)* seems to be best alternative. Similar to this for *OR* operation where *max (A, B)*is the solution suggested. Eventually, the operation *NOT A* which is equivalent to the operation *1-A* is defined, as shown in figure 13.

A	B	min(A,B)
0	0	0
0	1	0
1	0	0
1	1	1

AND

A	B	max(A,B)
0	0	0
0	1	1
1	0	1
1	1	1

OR

A	1 - A
0	1
1	0

NOT

Figure 13. Boolean logic in fuzzy logic

In addition, since there is a truth value between *0* and *1* there should be a function to define them. Figure 14 shows the value for *A AND B*, where different truth functions are applied. The upper figure depicts the plots for two-valued logic in contrast to the lower figure which is for the multi-valued logic. Therefore, based on these three fuzzy logical operations (*AND*, *OR* and *NOT*) any formation in fuzzy sets can be analysed.

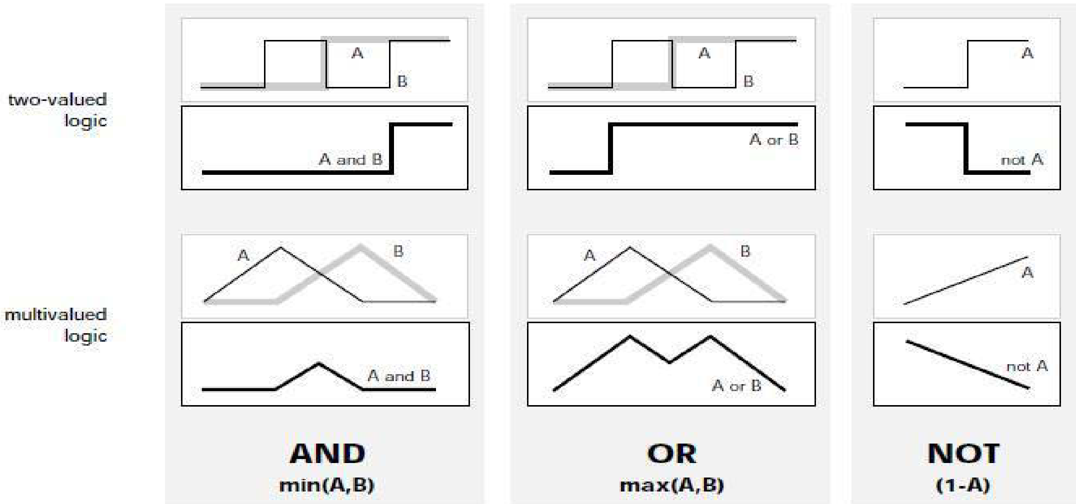


Figure 14. Plot of two fuzzy sets employed to create one fuzzy set

7.5.3.1. Additional fuzzy operators

The analogy between two-valued and multi-valued logical operations is for *AND* (fuzzy intersection or conjunction), *OR (*fuzzy union or disjunction), and *NOT* (fuzzy complement) have been defined so far, *AND* being equivalent to *min function*, *OR* to *max function* and *NOT* to additive complement. Generally, most fuzzy logic applications improvise these operations.

The intersection of two fuzzy sets *A* and *B* is specified by a function *T* which combines two membership grades as shown below:

$$\mu_{A\cap B}(x) = T(\mu_A(x), \mu_B(x)) = \mu_A(x) \otimes \mu_B(x); \tag{9}$$

where$\otimes$ is a binary operator for the function *T*. These fuzzy intersection operators, usually known as *T-norm* (Triangular norm) operators, meet the basic obligations.

A *T-norm* operator is defined below:

$$
\begin{gathered}
\textit{boundary}\text{: } T(0, 0) = 0,\ T(a, 1) = T(1, a) = a \\
\textit{monotonicity}\text{: } T(a, b) <= T(c, d) \text{ if } a <= c \text{ and } b <= d \\
\textit{commutativity}\text{: } T(a, b) = T(b, a) \\
\textit{associativity}\text{: } T(a, T(b, c)) = T(T(a, b), c)\ .
\end{gathered} \tag{10}
$$

The first requirement fulfils a generalized form of crisp sets. The second requirement indicates that a decrease in the membership values in *A* or *B* could not provoke an increase in the membership value in *A* intersection *B*. The third requirement indicates the irrelevance of the operator to the order of the fuzzy sets. In the end, the fourth requirement takes the intersection of any number of sets. Like fuzzy intersection, the fuzzy union operator is indicated by the *S* function:

$$\mu_{A\cup B}(x) = S\big(\mu_A(x), \mu_B(x)\big) = \mu_A(x) \oplus \mu_B(x)\ ; \tag{11}$$

where $\oplus$ is a binary operator for the function *S*. These fuzzy union operators *T-conorm* (or *S-norm* operators) meet the following criteria:

$$
\begin{gathered}
\textit{boundary}\text{: } S(1, 1) = 1,\ S(a, 0) = S(0, a) = a \\
\textit{monotonicity}\text{: } S(a, b) <= S(c, d) \text{ if } a <= c \text{ and } b <= d \\
\textit{commutativity}\text{: } S(a, b) = S(b, a) \\
\textit{associativity}\text{: } S(a, S(b, c)) = S(S(a, b), c)\ .
\end{gathered} \tag{12}
$$

The proof of these basic requirements is similar to the *T-norm* operator.

T-norms and dual *T-conorms* have been established to vary the “*gain*” on the function making it very restrictive.

7.5.4. If-Then Rules

Fuzzy sets and fuzzy operators are exclusively popular terms in fuzzy logic. Conditional sentences, if-then rules make fuzzy logic more practical.

A fuzzy if-then rule has the below form:

If x is A then y is B ;

Where A and B are linguistic values introduced by fuzzy sets on the universes of discourse of x and y. The if-part of the rule, "*x is A*" known as the *antecedent* and the then-part, "*y is B*" is the *consequent* or conclusion. A good example is the rule below:

If service is good, then tip is average ;

where the antecedent is a linguistic term indicating a single number between *0* and *1* in contrast to the consequent which maps the fuzzy set B to the output variable y. Therefore, the term "*is*" gets used in phrases, the antecedent and the consequent. In *MATLAB* language, this is the difference between a relational format where "==" is used and a variable assignment where "=" is used. Or in other words:

If service == good then tip = average ;

So the input to if-then rule is the input variable (*service*) and the output is the fuzzy set (*average*).

The if-then rule consists of several distinct sections: first section considers the antecedent (which takes into account fuzzifying the input and involves fuzzy operators) and second section considers the consequent (*implication*). For binary logic, the if-then rules are simple. If the antecedent is true then the precedent will be true as well.

If the antecedent is true to some extent, then the consequent is true to that same extent. For example:

In binary logic: $p \rightarrow q$ (p and q are either true or false)

In fuzzy logic: $0.5p \rightarrow 0.5q$ (partial antecedents are partially involved)

The antecedent of a *if-then* rule is capable of having multiple sections:

If the sky is grey and the wind is strong and the barometer is falling, then...

In which all the multiple consequents are influenced by the antecedent. The procedure in which the consequent is influenced by the antecedent is discussed further in this chapter. The consequent assigns a fuzzy set to the output. The fuzzy set is assigned to a degree modified by the antecedent by means of *the implication function*. *Truncation* using the *min function* is the most popular output modifying for the fuzzy sets in which the fuzzy set is chopped off, as shown in figure 15. *Scaling* using the *prod function* is another method, in which the output fuzzy set is squashed. Both methods are presented in the fuzzy logic toolbox.

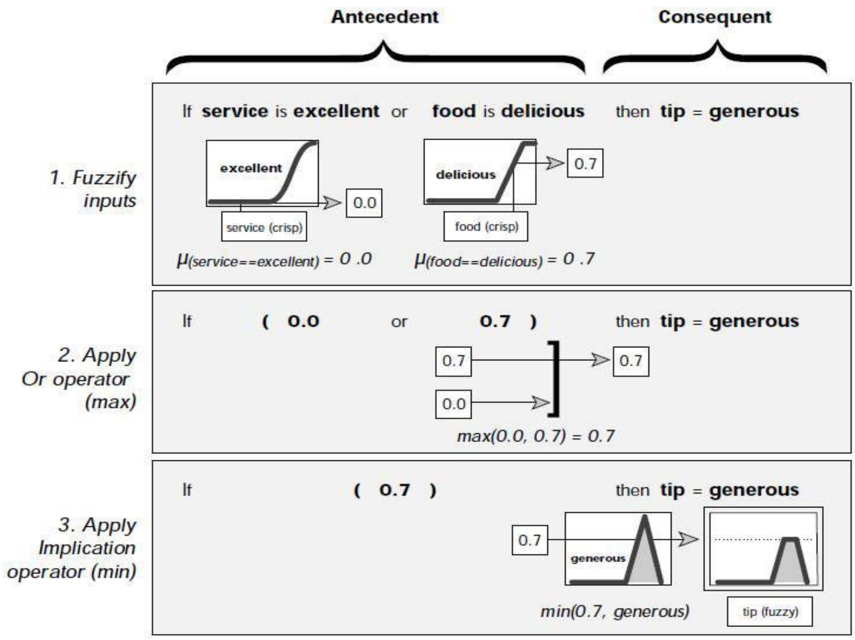


Figure 15. Fuzzy IF-THEN rules for "dinner at restaurant" example

7.5.4.1. If-Then rules in summary

There are three steps when defining the if-then rules:

1. Inputs need to be fuzzified

All fuzzy terms in the antecedent are transformed into a membership degree between *0* and *1*.

2. Fuzzy operator is applied

Fuzzy logic operators are applied to the antecedent to assign it to a number between *0* and *1*.

3. The implication process is applied

The consequent of the if-then rule allocates a fuzzy set to the output. This fuzzy set is truncated based on the implication method applied.

When defining a particular case in fuzzy logic language using fuzzy if-then rules, one rule is not effective. It is required that several rules be defined. The output of each rule is a fuzzy set. In the end, the final output for all the fuzzy sets is a single crisp number. In which first the output fuzzy sets for each rule is *aggregated* into an output fuzzy set. In the next step, this fuzzy set is *defuzzified* or transformed into a single number. The entire procedure is explained in the following section.

7.5.5. Fuzzy inference systems

Fuzzy inference systems match the membership functions of the fuzzy inputs to the membership functions of the fuzzy output using if-then rules and extracting a final single number through *defuzzification.*

The application of fuzzy inference systems is quite wide; control automation systems, classification of data and modelling. Therefore it has been given several names: *fuzzy-rule-based system, fuzzy associative memory, fuzzy logic controller, and simply fuzzy logic systems.*

7.5.5.1. "Dinner at restaurant" example

The fuzzy logic application for the aforementioned example, "dinner at restaurant" is explained in this section. Service and food are the two inputs and the tip paid to the waitress is considered as the output. There are three rules matching the inputs to the outputs, in which all rules are evaluated in parallel using fuzzy reasoning. The results of the rules are combined and distilled through the *defuzzification* process. The final result is a crisp, non-fuzzy number which is the output, in this example, the tip. The description of the fuzzy inference for this example is shown in figure 16. Each of the fuzzy inference terms are defined further in this chapter.

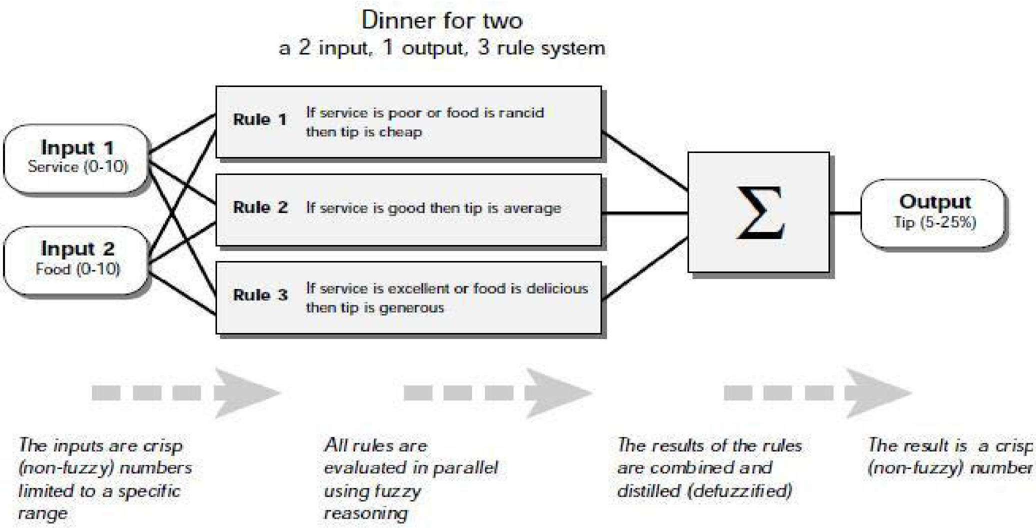


Figure 16. Fuzzy Rules for "dinner at restaurant" example

Step 1. Fuzzify Inputs

The first step is to define the inputs and assign the membership functions which are the degree the inputs belong to the fuzzy sets. The input is in the universe of discourse of the input variable and the output is always between *0* and *1*. Therefore, the inputs and outputs need to be *defuzzified*. The example in this section for the "dinner at restaurant" uses fuzzy membership functions to map the inputs to the different linguistic terms. For example, when the input is food and the food is delicious, based on the delicious membership function curve, the extent to which the food is delicious is defined. This input is *fuzzified* with the fuzzy operators and for a supposed food (rated from *0* to *10*) fitting the linguistic term "delicious", the result of *fuzzification* for the rate of *8* in the food is equivalent to *0.7* based on the defined membership function.

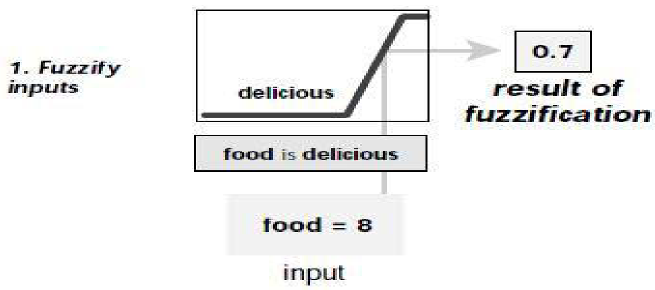


Figure 17. Fuzzify inputs for "dinner at restaurant" example

Step 2. Application of Fuzzy operator

After the input *fuzzification* step, each part of the antecedent in the fuzzy if-then rule is satisfied to a certain degree for every rule. If there is more than one part in the antecedent, the fuzzy operator estimates this degree which is a number allocated to that particular rule. This number is considered in the evaluation for the final output function. The inputs for a fuzzy operator are membership values whilst the output is a crisp number.

As mentioned in the previous sections, a well-defined method can be a substitute for the fuzzy logic operations, *AND* or *OR*. In the fuzzy logic toolbox, two functions are defined for *AND* operation which are: *min(minimum)* and *prod(product)* and two functions are defined for the *OR* operation which are: *max (maximum)*, and the probabilistic *OR* method (*probor)* or *(the algebraic sum)*. The equation for this method is given below:

$$probor(a,b) = a + b - ab. \tag{13}$$

The "dinner at restaurant" example for the *OR* operation in the fuzzy logic toolbox, maximum, is presented below. The two parts of the antecedent have two membership functions which based on two inputs in the universe of discourse; two fuzzy membership values *0* and *0.7* are resulted. For the fuzzy *OR* operation, the maximum of these two is considered, which is *0.7*. Therefore, the result of fuzzy operation for this rule is *0.7*, as shown in figure 18.

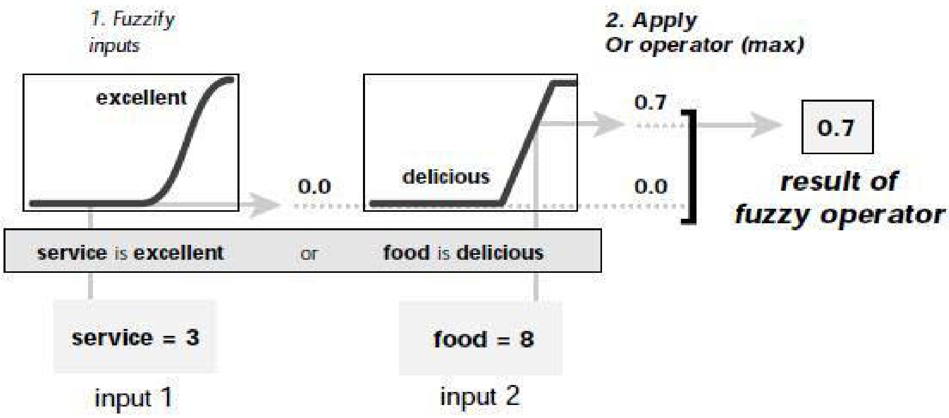


Figure 18. Applying Fuzzy operator for "dinner at restaurant" example

Step 3. Implication method Applied

Prior to applying the implication method, the weight of each rule must be defined (a number between *0* and *1*) which is provided by the antecedent. This weight is assumed based on weighing one rule relative to the others. For the "dinner at restaurant" example, this weight is 1. The implication method is applied based on the single number provided by the antecedent and the output is a fuzzy set. For each rule, the implication is performed. The implication operator *min* (minimum) which truncates the output fuzzy set and *prod* (product) which scales the output fuzzy set are applied, as shown in figure 19.

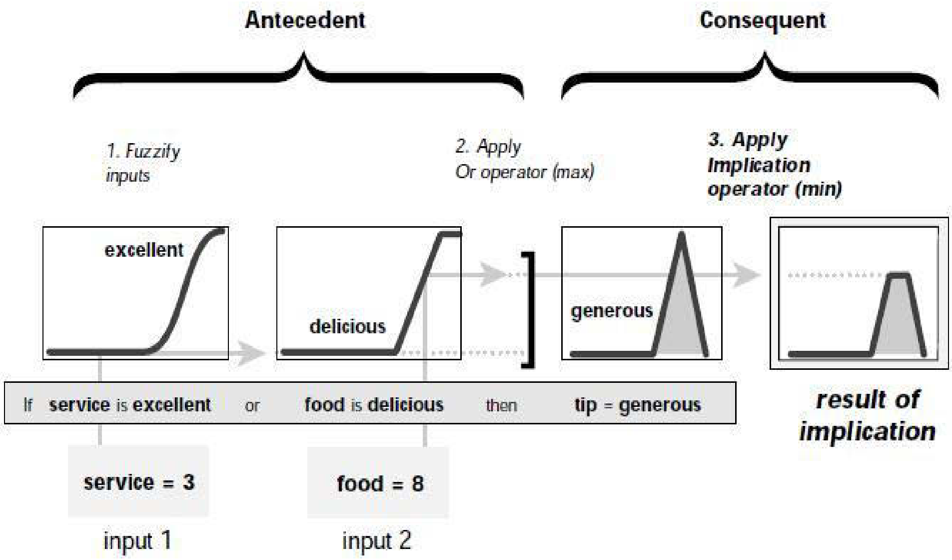


Figure 19. Applying Implication method for "dinner at restaurant" example

Step 4. Aggregation of the Outputs

In the aggregation step, the outputs of each rule are unified, in which all the fuzzy sets for the output of each rule is combined into a single fuzzy set which is provided to the *defuzzification* step. Therefore, after the implication operation, in this example *min* (minimum) is applied. The result of the implication for each rule which is the truncation of the output function is aggregated for each output variable in each rule. This aggregation process is changeable; therefore the execution order for each rule is not very significant. The method for aggregation is built in the fuzzy logic toolbox. They are: *max* (maximum), *probor* (probabilistic or) and *sum* (sum of the output set of each rule).

Figure 20 is a typical example of the aggregation of all outputs for the "dinner at restaurant" example.

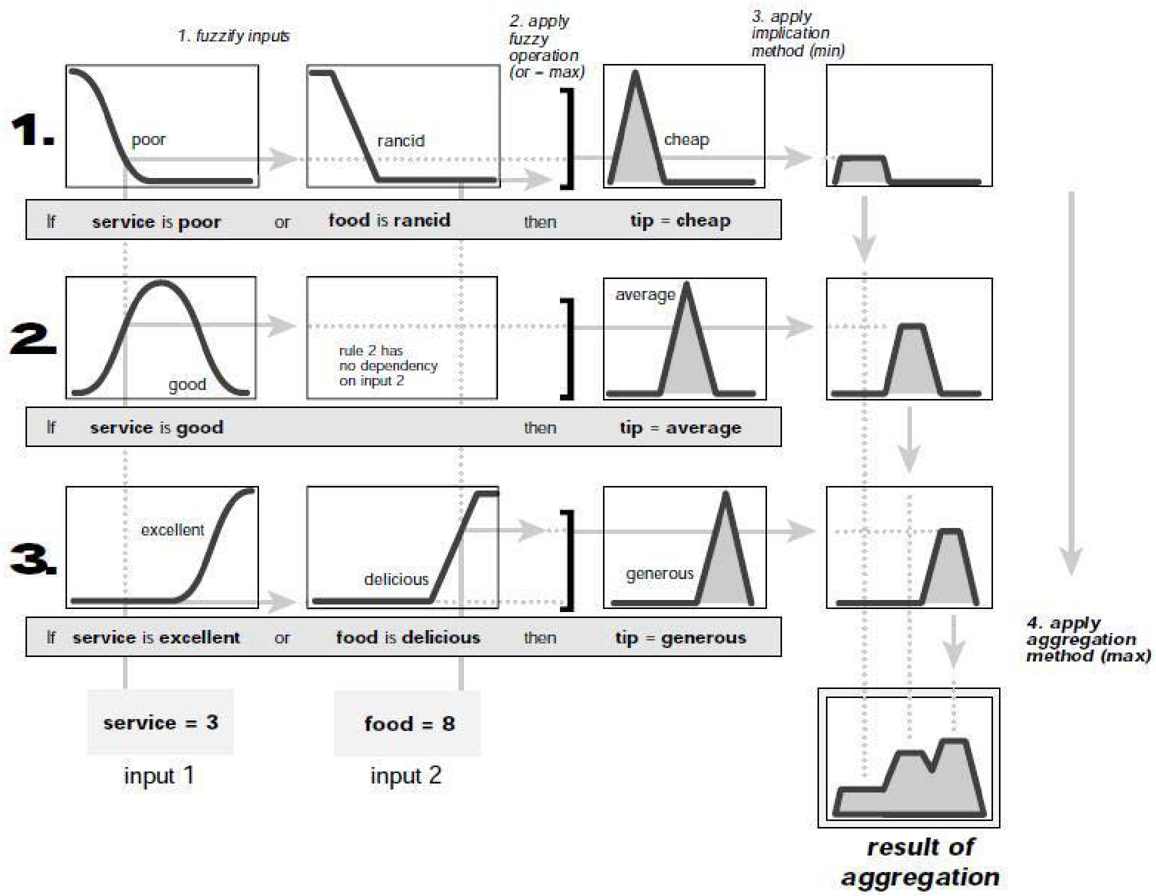


Figure 20. Aggregating all outputs for "dinner at restaurant" example

Step 5. Defuzzification of the aggregated output

The aggregated output from the previous step is a fuzzy set to be *defuzzified* in this step in which the *defuzzified* output is a single crisp number. Therefore, the *defuzzification* process takes a fuzzy set as the input and returns a single number to the output. The *defuzzification* method which is the most common is the centroid method, wherein the centre of the area from the aggregation step is returned. For the "dinner at restaurant" example, the centroid is chosen as the *defuzzification* method and the crisp output number is the final output, which is the tip given based on the food and service provided as the inputs, as shown in figure 21. There are other *defuzzification* methods largest of maximum, smallest of maximum and middle (average) of maximum.

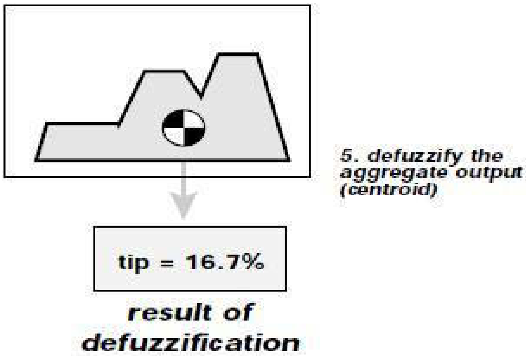


Figure 21. Defuzzification for “dinner at restaurant” example

7.5.6. The Fuzzy inference diagram

In the fuzzy inference diagram, the processes of how all the aforementioned steps are performed are shown. The flow of information for this section is shown in figure 22. This flow proceeds from each of the inputs to the outputs and finally from all the outputs of all the rules defined to a single crisp number to be the final *defuzzification* output. The MATLAB implementation of this diagram is shown in the fuzzy logic toolbox (J.S.Roger Jang).

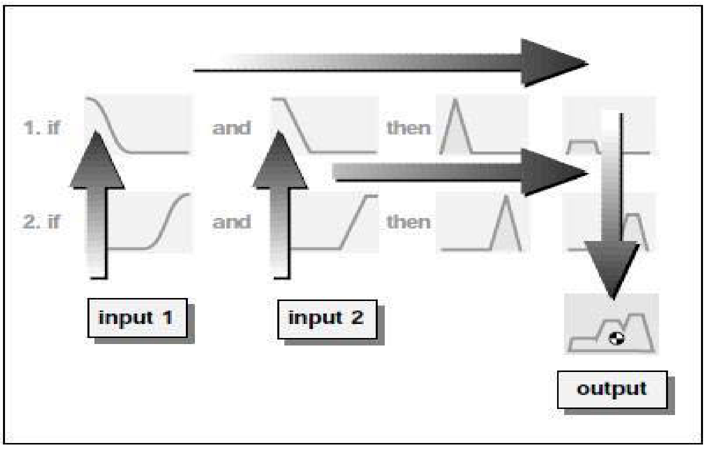


Figure 22. Defining the Fuzzy inference diagram