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PD and Fuzzy Logic Control for Earthquake Resilient Structures

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ABSTRACT: This research was conducted within the framework of a National Science Foundation sponsored summer Research Experience for Undergraduate (REU) students. This research considers small-scale and mathematical models of simple one-story structures that are subjected to free and base-motion excitations and installed with and without passive damping devices to gain an understanding of their dynamic behavior while reviewing active and semi-active damping means being applied and researched today. Using computer programming and numerical methods, the goal is to understand and counteract catastrophic disasters to structures caused by earthquakes. The research is broken down into a number of MATLAB simulations and experiments in order to understand basic dynamic and control features required to design earthquake resilient buildings. These experiments include free vibration experiments to test for the stiffness of columns for different heights and to test for the natural frequency and damping ratio of a one-story structure under different mass loads. Active PD control was then applied to an experimental system experiencing accelerations attributed to the Northridge 1994, Kobe 1995, El Centro 1940, and Mendocino 1992 earthquakes. Robustness comparisons were made between (1) P control; (2) D control; and (3) PD control for the above earthquake inputs to the shaker. A fuzzy logic controller was developed to effectively control transient vibrations. The uniqueness of this control concept is that the fuzzy control continuously varies the damping characteristics of a semi-active tuned mass damper (TMD). It was concluded that a fuzzy logic based TMD was more effective than a regular passive TMD, by providing half the settling times. © 2012 Wiley Periodicals, Inc. *Comput Appl Eng Educ*; View this article online at wileyonlinelibrary.com; DOI 10.1002/cae.20540

Keywords: seismic response; tuned mass dampers; active control; passive control; earthquake resilient structures; fuzzy logic control

INTRODUCTION

As part of its strategic plan, in 2006 the College of Engineering and Applied Science at University of Cincinnati decided to focus on four research thrust areas: (1) Sustainable Urban Environments (SUE), (2) Nano-Scale Science and Technology (NSST), (3) Emerging Energy Systems (EES), and (4) Emerging Intelligent Autonomous Systems (ELAS). Each is an interdisciplinary research and education effort led by the College of Engineering and Applied Science which includes participation from the Colleges of Arts and Sciences (A&S), Design Archi-

ture Art and Planning (DAAP), Education Criminal Justice and Human Services (CECH), and Medicine (CoM) as well as industrial and international collaborations. Each year Research Experience for Undergraduate (REU) projects are selected in these research thrust areas which are part of ongoing funded research grants, having well-defined goals and objectives to be completed by the REU teams during the 8 summer weeks. In the summer of 2010, one of the REU topics offered was “Dynamics and Control of Earthquake Resilient Structures” mentored by Profs. Kukreti and Cohen and Mr. Edalath, a graduate student. The first three co-authors comprised the REU team who worked on the above topic and in this article, the highlights of the research effort are presented. Before proceeding with the details of work done by students, the mentor perspective is provided on goals, equipment, and expected outcomes.

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Goals and Objectives of the Project

Students will primarily be made aware of the structural challenges posed by seismic excitation of buildings. It is anticipated that students will gain a better understanding and hands on knowledge on the following:

- An assessment of the damage incurred by major earthquakes in the last couple of decades.
- Dynamic nature of the seismic excitation, measurement techniques and response spectra analysis.
- Inherent damping in structures and the role of damping in the dynamic response.
- Techniques to enhance building resilience.
 - Passive approaches
 - Active approaches

Equipment and Computer Resources

- *Earthquake Structures Laboratory (Dr. Kukreti's Lab):* Use available test bench and equipment to conduct-free vibration tests and examine damping effects. Equipment includes shake table, spring mass model, LVDT sensor, dampers, data acquisition system, and monitor. In this lab, students will additionally develop and put together *their own shake-table and structural configurations* to examine passive means of seismic vibration suppression. Additional resources requirement include shake-table, Lego[®] set for structural models, and strain gauge and accelerometer for response measurement.
- *Intelligent Aerospace Systems Laboratory (Dr. Cohen's Lab):* Work with the Quanser[®] based shake table and the active mass damper and computer/MATLAB configuration in the lab.

Expected Outcomes

- *At the end of 8 weeks:* Students should be able to turn in a comprehensive report which includes the following sections: Introduction and Motivation; Literature survey; Mathematical modeling of structural dynamic problem; Passive means—Computational & experimental results; Active means—Computational & experimental results; Summary.
- A presentation/poster which summarizes the above.
- A formatted article to be submitted at a student conference.

BACKGROUND

Earthquakes are devastating natural disasters that many engineers need to take into account when designing and contracting civil infrastructure systems. The energy suddenly released from the Earth's crust during an earthquake creates seismic waves that may become catastrophic. The effects of such an event can lead to building damage, fires, and even loss in human lives. Today, when a building is constructed, there are several codes and regulations that need to be met so as to ensure that a structure will withstand external vibration such as those from earthquakes [1–4]. A background on engineering vibration and structural dynamics is provided by Inman [5].

There have been many significant earthquakes that have made an impact on society over the years. In the year of 1994 in Northridge, CA, an earthquake of magnitude 6.7 took place causing 60 lives to be lost and was estimated at over \$15 billion in property loss [6]. Soon after, an even more destructive earthquake occurred during 1995 in Kobe, Japan. This earthquake measured a magnitude of 6.9 and ruptured directly downtown. This earthquake resulted in over 5,400 deaths and had damages estimated at \$150 billion [7]. During the few years between 1995 and now, structures are becoming increasing taller. In order to prevent damages such as those that occurred due to the Kobe earthquake, it would be safe to assume that the safety of such buildings is crucial.

One of the ways to counteract seismic forces in a building due to an earthquake is to implement control systems into them. These systems are designed using a method called aseismic design. The basis for an aseismic design is that a structure should be able to resist the forces of previous earthquakes, such as the ones experienced in Northridge and Kobe. Presently, there are four main ways to classify these systems: active, passive, semi-active, and hybrid control systems; for this research, the first three will be the focus. In a passive control system, or tuned mass damper (TMD), there is no external energy force required to operate the controller [8]. All that is needed is the excitation of the earthquake causing the structure to move naturally. The result of the movement will cause the system to respond, which will be dependent upon the initial design of the structure, thus being “tuned” to the structure. Being “tuned” means the TMD and the structure's fundamental frequency are the same; therefore, as the structure has a dynamic response, the TMD will act in the opposite direction. The system will then absorb some amount of the energy. In contrast, active systems incorporate an external energy source that may run actuators and/or sensors. These sensors read the excitation of the building and respond by means of an actuator. When incorporating a semi-active system into a structure an external energy source is still needed, but the power consumption is much less than an active system. Here, batteries may be used which will aid in times when power is an issue. In addition, these systems do not include any mechanical devices and may be known as “controllable passive devices” [9]. The external power is used to change the parameters of the controller such as the damping coefficient. This study will develop insight into the dynamic behavior of simple structures when subjected to “earthquake-like” excitations while investigating the trends in structural control systems [10].

A number of researches have already been conducted on structural dynamics, earthquake resistant designs for structures, and fuzzy logic. Using fuzzy logic in improving the dynamic properties of structures is a new field that still has a lot of area in it left unexplored, one of the main reasons for this being that fuzzy logic itself is a relatively new concept. A lot of people have come up with various techniques and methodologies to introduce and teach fuzzy logic and structural dynamics to beginners in this field. Ackayol et al. [11] in his article discuss about a new educational tool which helps in teaching fuzzy logic to undergraduate and graduate students. Mosqueda et al. [12] developed an all inclusive web resource that links the study of earthquakes and engineering design to middle grade science and mathematics students. Researchers have also come up with different computer programs and Internet applications that help students and researchers in conducting virtual dynamic

experiments on structures subject to external disturbance. Gao et al. [13] and Sim et al. [14] have developed a series of java powered virtual laboratory that provides a means for online interactive structural dynamics experiments for undergraduate and graduate education. Clarke [15] developed a software “ENGLITHA” (Earthquake Nonlinear and General Linear Time History Analysis) which caters for single degree of freedom nonlinear systems emphasizing degrading response as in-cycle strength degradation, progressive cycle strength degradation, general stiffness degradation, and pinching degradation, or combinations of these, under earthquake ground motions. Elgamal et al. [16] developed a website which allows real-time video monitoring, control, and execution of bench-top shake-table experiments for educational and research purposes. Kuester and Hutchinson [17] in their article presents a virtualized laboratory for earthquake engineering education that utilizes virtual reality technology to capture and disseminate the results of shake table experiments.

Apart from the above researches which basically helps in introducing fuzzy logic and structural dynamics to beginners and provides the tools which helps in conducting small and simple virtual dynamic experiments on structures, researchers have also come up with new control strategies utilizing semi-active methods and fuzzy logic to enhance the earthquake resisting property of a building. Semi-active techniques have been utilized to enhance the performance of a base isolator by supplementing it with a semi-active damper [18] and to control the vibrations in a nonlinear coupled bridge system [19]. Given that the research mentioned in this article uses fuzzy logic to develop the control algorithm to control the damping coefficient of a semi-active damper, it is worth mentioning that numerous other researches have also been conducted to develop control algorithms for semi-active dampers. Some of the algorithms so developed are the clipped-optimal control algorithm [20], modified clipped-optimal control algorithm [21], maximum energy dissipation algorithm [22], and modulated homogeneous friction algorithm [23]. Jansen and Dyke [24] in their article conduct a comparative study of the different control algorithms for semi-active devices. Being a new and emerging area in the field of controls, semi-active technology has not been implemented in a lot of structures. However, passive and active controls are being used in buildings to resist them against wind and earthquake forces. In this effort, we examine the behavior of building structures when experiencing earthquake motions and tests need to be performed to employ effective active control strategies based on fuzzy logic control.

RESEARCH GOALS AND OBJECTIVES

The primary goal of the project is to investigate the trends in structural isolation and control to create more effective aseismic designs. To achieve this goal the following four objectives have been identified for the research project:

- (1) Understand free and forced vibration characteristics and thus the dynamic behavior of a one-story building to improve its earthquake resistance capability.
- (2) Explore how the structural configuration of a building affects its earthquake resisting capabilities.
- (3) Study an active proportional-derivative (PD) controller to learn how to improve seismic resistance ability.

- (4) Use fuzzy logic to design a semi-active TMD to create a faster and safer dynamic response from the structure.

RESEARCH TASKS

To achieve the objectives identified for the study, the following five research tasks are undertaken:

- (1) Conduct free vibration tests on one-story models of various stiffness and mass to determine natural frequency, stiffness, and damping characteristics of the structure.
- (2) Conduct forced vibration tests on a one-story model to study the effects of resonance. Also, explore the impact of a passive damping device on the dynamic response.
- (3) Work in the Aerospace Lab to conduct tests with different known earthquakes on a one-story structure with a PD controller attached to it.
- (4) Create a model of a one-degree of freedom (DOF) system within MATLAB and conduct free vibration tests on this model with and without a TMD.
- (5) Use fuzzy logic to control the damping coefficient of the TMD and thus enhance its performance.

While the first two tasks were imperative in developing a vital understanding of the basic concepts, this article focuses on reporting on tasks 3–5 which falls within the scope of the journal.

ACTIVE MASS DAMPER BASED CONTROL OF AN EXPERIMENTAL STRUCTURE UNDER SEISMIC LOADS

The Quanser[®] Linear Motion Servo Plant: Active Mass Damper-One Floor (AMD-1) is used to design a control system that will dampen a one-story structure undergoing a dynamic excitation. This experiment was conducted in the Aerospace Lab. This experiment will show how controls are used and implemented using an active mass damper cart (the cart is the mechanical device for this equipment). More in depth, a look into proportional-derivative (PD) controllers will be the focus in developing and understanding how active controllers are used in modern day structures. The objective of this simulation is to create the best damper using active controls. Changing the parameters used in the control will aid in the understanding of the importance of each. As a structure experiences a dynamic disturbance, the PD controller should respond and to return the structure to equilibrium in the safest and fastest possible way.

Active mass dampers (AMD) require external energy, which process the data from sensors and responds accordingly. In this simulation, these controls are managed by two different parameters: proportional and derivative. A proportional gain parameter (K_p) has the effect to reduce the rise time, the time it takes the structure to return to its equilibrium position. The derivative gain parameter (K_d) has the effect to increase the stability of the structure while reducing overshoot and improving the temporary response. Together, these parameters make a PD controller.

These controllers are dependent on each other; increasing one will change the other. This is where the strategizing portion of the research occurs. For this exercise, a Quanser[®] Linear

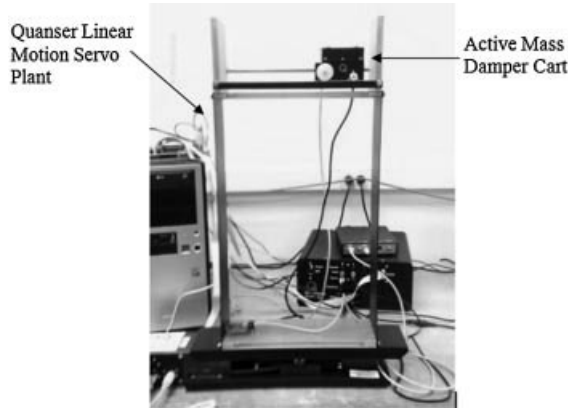


Figure 1 Linear motion servo plant with active mass damper cart.

Motion Servo Plant: Active Mass Damper-One Floor (AMD-1), shown in Figure 1, and the LabView Program are used. The active mass damper is actuated by means of a cart that moves, and thus applies a force opposite of the moving structure.

This LabView program, which was previously installed, replicates the ground motion acceleration response history for three earthquakes, including, Northridge 1994, Kobe 1995, El Centro 1940, and Mendocino 1992 earthquakes. The best PD controller contains both proportional and derivative components, while P controller contains only the proportional component and D controller contains only the derivative component. In this experiment it was found that the PD controller performs its best when the K_p and K_d values are 17.5 and 3.4, respectively. These numbers will be used at the end of the steps listed below which show the significance of the parameters in a control.

- (i) Make sure the LabView program and one-story structure are ON.
- (ii) Eliminate the derivative parameter (K_d) to see the effects of a proportional parameter (K_p). Select the CONTROLS tab and set K_d to "0" and K_p to "20" as the first run.
- (iii) Click on the NORTHRIDGE tab and turn the cart ON.
- (iv) Save the file under a distinct name for this simulation (i.e., Northridge_Kp0_Kp20).
- (v) Run the replicated earthquake for about 25 s (displacement is being reviewed and occurs in the first 20 s).
- (vi) Return to the CONTROLS tab and lower K_p to "19" (Intervals can be changed according to preference; however, smaller intervals allow for better results). Remember that the derivative parameter is eliminated (keep K_d at "0") and save the file as another distinct name.
- (vii) Repeat steps (ii) to (vi) until K_p is "0."
- (viii) Open $K_d = "0"$ files in Excel[®] and find the absolute maximum displacement for the different values of K_p used. The best value of K_p is the one that produces the least absolute maximum displacement of the structure.
- (ix) Next, repeat the steps keeping the value of $K_p = "0"$ and increasing the value of K_d from "0" to "5"

(intervals can be changed according to preference, however, smaller intervals allow for better results).

- (x) Once completed, open the $K_p = "0"$ files in Excel[®] and find the absolute maximum displacement for the different values of K_d used. The best value of K_d is the one that produces the least absolute maximum displacement of the structure.
- (xi) The parameters of the controller that produce the least maximum absolute displacement will be labeled as being the best.
- (xii) Compare the best P, D, and PD controllers found for the Northridge earthquake.
- (xiii) Compare the best P and D controllers found for Northridge on the other replicated earthquakes to test effectiveness.

After finding the best P and D controllers independently, their dependence on one another was verified. When P or D acted alone on the structure, the response was worse than when acting together. This shows that to create a controller that will be the most efficient, both P and D components must be present. They are dependent on each other and thus work best when acting as a single controller. Future research in PD controllers may involve implementing a new concept called fuzzy logic [25] in it to enhance its performance, which will be explored in the following section.

PASSIVE TMD AND FUZZY LOGIC CONTROL USING MATLAB SIMULATIONS

MATLAB is an advanced technical computing language. For this research, the use of MATLAB's data visualization, data analysis, and numeric computation is used to understand the effects of ground motion excitation. A toolbox within MATLAB known as fuzzy logic allows the advancement of control design while testing and measuring how effective the damper created will be. Simulations are created using the aid of MATLAB in order to test the effectiveness of different passive and semi-active control devices such as TMDs, fuzzy logic based TMDs, and base isolators.

Computers were originally designed to compute functions and feedback data. They only understand the concepts of TRUE/FALSE. Fuzzy logic is the function that allows a computer to take into effect the "gray" scale of life. Some things may be considered as partly true and partly false. Take, for example, a compartment with a fan. Suppose the ideal temperature needed for this compartment is 70°F. Anything below this set temperature is considered too cold and anything above is considered too hot, those include 69°F and 71°F, respectively. A control of fan speed will only consider three membership functions in this case: slow down, stay constant, or speed up. These membership functions allow for measured variables to be converted to linguistic terms. The way the user shapes and places these membership functions determines how the values will be converted into linguistic terms.

In the real world, this could cause major disruptions. What if the fan slows down too much because the compartment was not in fact TOO cold? Now the control must counteract itself and hopefully come to equilibrium, which wastes time. Computers need to understand the "fuzzy" portions between the

TRUE and FALSE, and is where fuzzy logic will aid in this research.

In fuzzy logic, one could break the membership functions of the compartment from being TOO COLD, COLD, MODERATE, HOT, TOO HOT . . . to many more as following options:

- IF temperature IS too cold THEN stop fan
- IF temperature IS cold THEN slow down fan
- IF temperature IS moderate THEN keep fan constant
- IF temperature IS hot THEN speed up fan
- IF temperature IS too hot THEN gust the fan

These functions allow the compartment to steadily, and safely, reach its final destination becoming just right.

This logic will be used to create a better TMD, where economic and safety concerns hold equal weight. This TMD will be tuned in order to stop the vibration within a structure in the least amount of time, roughly 50% faster than passive TMDs.

One-Story Structure Simulation Without a Control Device

A MATLAB simulation of a one-story structure without any controls in it is conducted to study the response of the structure to free vibrations and harmonic ground motions. These results will help in determining the effectiveness of a controller placed in this structure by comparing the response of the structure with a controller to the results obtained in this simulation.

The equations in MATLAB are derived using the equation of motion for a one-story structure subject to free vibration, which is given by Equation (1):

$$m\ddot{x} + c\dot{x} + kx = 0 \tag{1}$$

where m is the mass, c the damping coefficient, k the stiffness, \ddot{x} the acceleration, \dot{x} the velocity, and x the displacement.

This equation is solved for acceleration, giving:

$$\ddot{x} = \frac{(-c\dot{x}-kx)}{m} \tag{2}$$

In order to implement these equations into MATLAB, certain parameters need to be defined. The parameters are defined as follows:

$$x(1) = \text{displacement}$$

$$dx(1) = x(2) = \text{velocity}$$

$$dx(2) = \text{acceleration}$$

The simulation is then set up within two m -files, a function file and an integrating file. The function file includes the equations of motion as represented by $dx(1)$ being velocity and $dx(2)$ being acceleration of the top of the structure, as shown below.

$$dx(1) = x(2);$$

$$dx(2) = (k * x(1) - c * x(2)) / m;$$

Then masses, stiffness', and damping coefficients are assigned to the structure such that:

- m = the mass of the structure = 1 kg,
- k = the stiffness of the structure = 200 lb/in., and
- c = the inherent damping present within the building = 5%.

The ode45 command in MATLAB is used to solve the ordinary differential equation of motion for known initial conditions. This gives the displacement and velocity response results for given input data, which can be used to plot their variation with time.

By running the simulation, it was found that with no control device attached to the structure, the structure damped, or came back to equilibrium in approximately 8 s, as shown in Figure 2.

One-Story Structure Simulation With Tuned Mass Damper

This simulation is done to see the best resting time that can be achieved by a simple TMD for a one-story structure. A TMD is attached to the top of the structure, which has a mass of one-tenth the mass of the structure and stiffness (denoted as k_2). Thus, this system is a two degree of freedom (2 DOF), which includes the movement of the top floor mass of the one-story structure and the movement of the mass of the TMD. The natural frequency of the TMD is tuned to the natural frequency of the structure by adjusting k_2 , the stiffness of the TMD.

Again, equations of motion for a freely vibrating structure is used, as given by Equation (3):

$$M\ddot{x} + C\dot{x} + Kx = 0 \tag{3}$$

where the variables, M , C , and K are 2×2 matrices and the equation of motion is given by Equation (4):

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \ddot{x} + \begin{bmatrix} c_1 + c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix} \dot{x} + \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} x = 0 \tag{4}$$

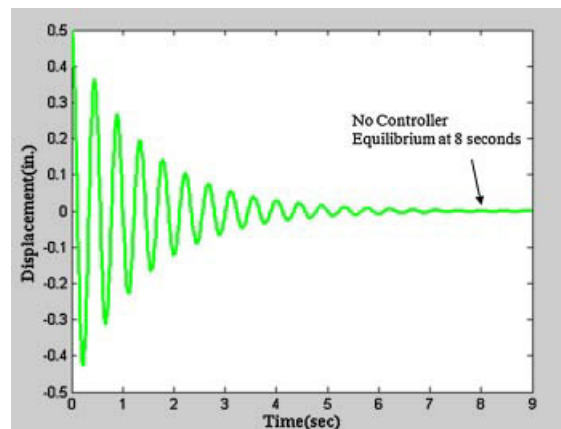


Figure 2 MATLAB simulation of a one-story structure with no control device. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

This can be expanded as a set of two ordinary differential equations, which are given as Equations (5) and (6):

$$m_1\ddot{x}_1 + (k_1 + k_2)x_1 - k_2x_2 + (c_1 + c_2)\dot{x}_1 - c_2\dot{x}_2 = 0 \quad (5)$$

$$m_2\ddot{x}_2 + k_2x_1 + k_2x_2 - c_2\dot{x}_1 + c_2\dot{x}_2 = 0 \quad (6)$$

where m_1 is the mass of structure, m_2 the mass of TMD, c_1 the damping coefficient of structure, c_2 the damping coefficient of TMD, k_1 the stiffness of structure, k_2 the stiffness of TMD, \ddot{x}_1 the acceleration of structure, \ddot{x}_2 the acceleration of TMD, \dot{x}_1 the velocity of structure, \dot{x}_2 the velocity of TMD, x_1 the displacement of structure, and x_2 the displacement of TMD.

The parameters for MATLAB used are as follows:

$x(1)$ = displacement of structure
 $dx(1) = x(2)$ = velocity of structure
 $dx(2)$ = acceleration of structure
 $x(3)$ = displacement of TMD
 $dx(3) = x(4)$ = velocity of TMD
 $dx(4)$ = acceleration of TMD

The simulation is then set up within two m -files, a function file and an integrating file. The function file includes the equations of motion as represented by $dx(1)$ being velocity of the structure, $dx(2)$ being acceleration of the top of the structure, $dx(3)$ being the velocity of the TMD, and $dx(4)$ being the acceleration of the TMD, as shown below.

$$dx(1) = x(2);$$

$$dx(2) = (k_2 * x(3) - (k_1 + k_2) * x(1) - (c_1 + c_2) * x(2) + c_2 * x(4)) / m_1;$$

$$dx(3) = x(4);$$

$$dx(4) = (k_2 * x(1) - k_2 * x(3) + c_2 * x(2) - c_2 * x(4)) / m_2;$$

The `ode45` command in MATLAB is again used to solve the two set of equations of motion (Eqs. 5 and 6) to obtain the displacement and velocity response history of the top floor of the one-story structure and plot these against time. In order to find the best possible TMD the value for c_2 is changed until the optimal damping time is found.

This happened when the TMD had about 30% of critical damping which allowed the structure to come back to equilibrium in about 3 s, as can be seen in Figure 3. The passive TMD was able to settle the structure in 62% of the time taken for the structure to settle without a control device, as can be seen in Figure 3.

One-Story Structure Simulation With Fuzzy Tuned Mass Damper

After doing simulations to find the best TMD, the next step is to incorporate the idea of fuzzy logic into creating an even better TMD. Fuzzy logic is used to change the damping coefficient of the TMD in a controlled manner so that the structure comes to rest in a lesser time.

The equations of motion are the same as the previous simulation (Eqs. 5 and 6), with $dx(1)$ being velocity of the structure, $dx(2)$ being acceleration of the top of the

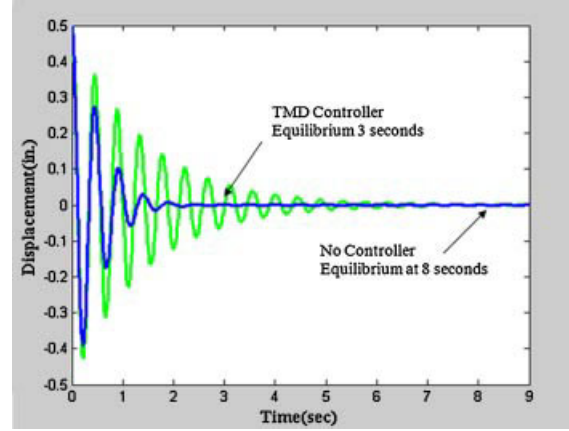


Figure 3 MATLAB simulation comparing one-story structure with no control device to one-story structure with TMD. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

structure, $dx(3)$ being the velocity of the TMD, and $dx(4)$ being the acceleration of the TMD being the parameters for MATLAB. The only change made is that “ c_2 ,” the damping coefficient of the TMD, is not set as a specific value. Rather, the value of “ c_2 ” at any given instance of time is determined by the fuzzy logic control algorithm.

Within the fuzzy logic toolbox there are inputs, outputs, and rules that are created. The inputs for the fuzzy logic controller created are displacement and velocity, the two characteristics of a structure that continually change during a seismic excitation. The output of the fuzzy logic controller is the damping coefficient of the damper, the “ c_2 ” value used in the above simulations.

Each input, displacement and velocity, are given five membership functions. Next, 25 rules are created to specify what output will match each input, which are specified in Table I.

After setting the rules, the shape of each membership function are adjusted in order to achieve the lowest settling time. At least a single second lower settling time from the non-fuzzy TMD is desired. The shapes of the membership functions are presented in Figures 4–6.

After finding the best fuzzy TMD, it was compared to the best non-fuzzy TMD to ensure that the fuzzy TMD had a better damping time. The displacement responses of the top floor mass of the one-story structure using fuzzy logic are presented in Figure 7. As can be seen from these figures, the fuzzy TMD settled in 1.5 s, 50% of the time taken by a passive TMD to settle.

Table I Table of Rules for Fuzzy Logic Based TMD Controller

Velocity	Displacement				
	Left far	Left	Equilibrium	Right	Right far
High positive	Small	Medium	Medium	Medium	Small
Positive	Small	Large	Large	Large	Small
Zero	Small	Large	Extra large	Large	Small
Negative	Small	Large	Large	Large	Small
High negative	Small	Medium	Medium	Medium	Small

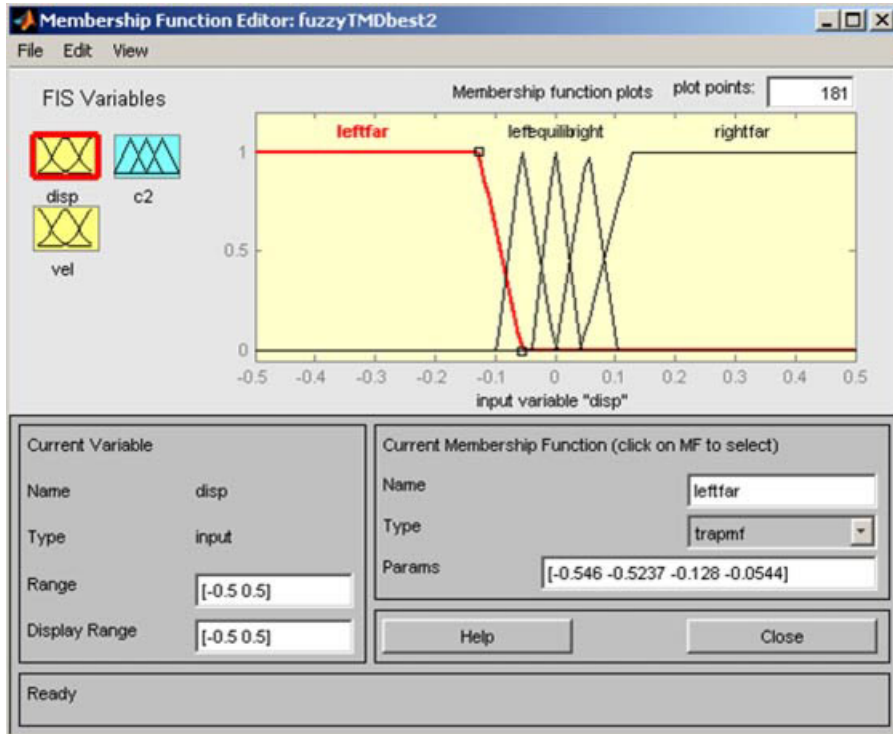


Figure 4 Displacement input membership functions for fuzzy logic TMD. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

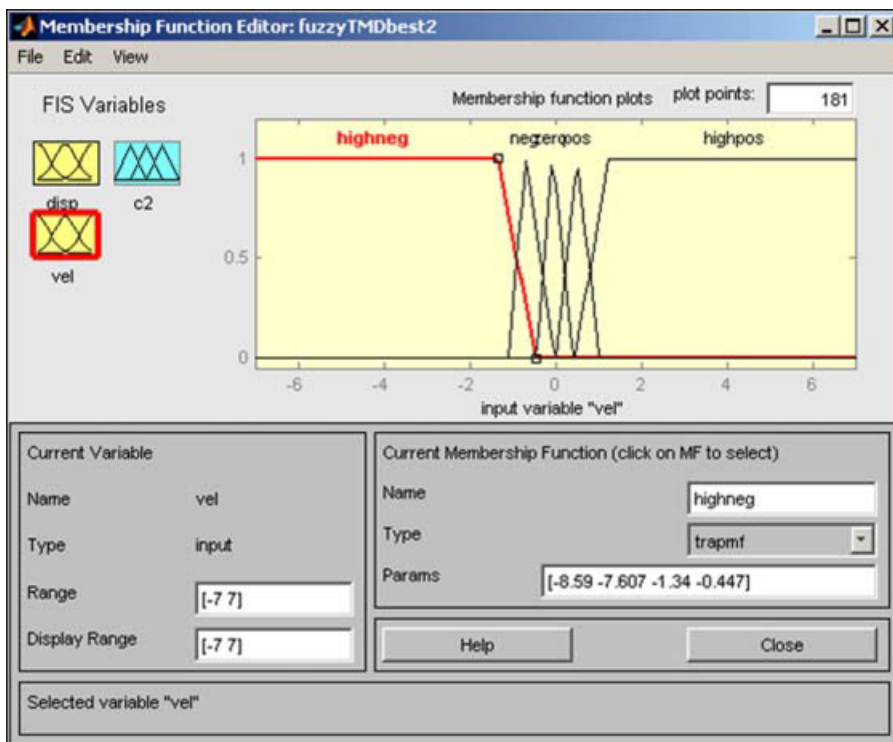


Figure 5 Velocity input membership functions for fuzzy logic TMD. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

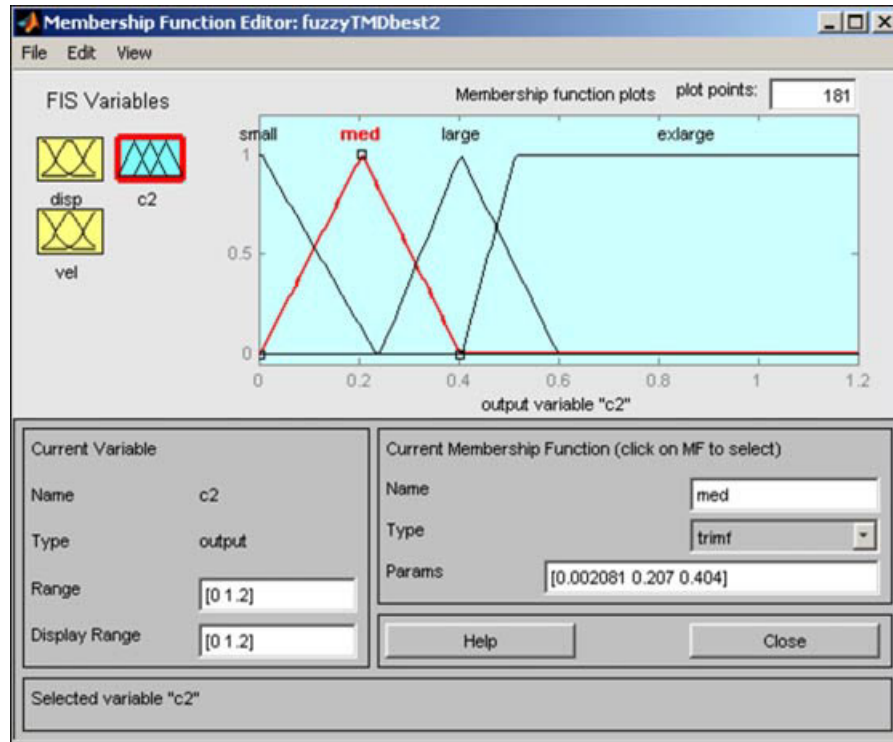


Figure 6 Damping coefficient (c_2) output membership functions for fuzzy logic TMD. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

One-Story Structure Robustness Test for TMD and Fuzzy TMD Controllers

After completing simulations to find the best passive TMD controller and the best fuzzy logic TMD controller, both of these controllers are tested for robustness. The robustness test is used to verify that the fuzzy logic TMD controller performs better than the passive TMD controller does, when conditions within the structure are changed. The changing characteristic tested within the structure is mass, where the original mass is 1 unit; the robustness test will test both controllers using a mass differential of $\pm 10\%$, that is, mass of 1.1 and 0.9 units, respectively.

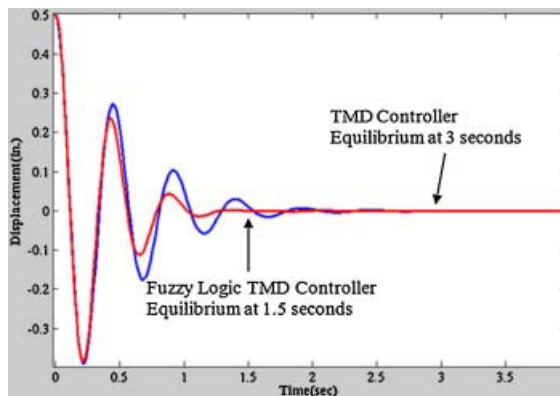


Figure 7 MATLAB simulation comparing one-story structure with passive TMD to one-story structure with semi-active fuzzy logic TMD. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

A structure's floor mass is comprised of a dead load (DL) and a live load (LL). The DL, the mass of the office supplies, desks, equipment, etc. remains constant while the LL is variable. The LL will vary in a structure depending on how many people occupy it. For instance, an office building will be empty at night making the LL about equal to zero and thus reducing total mass of the structure. There may also be times when the LL will go beyond its normal range, such as if there is a party going on in the structure. While we trust a TMD to perform

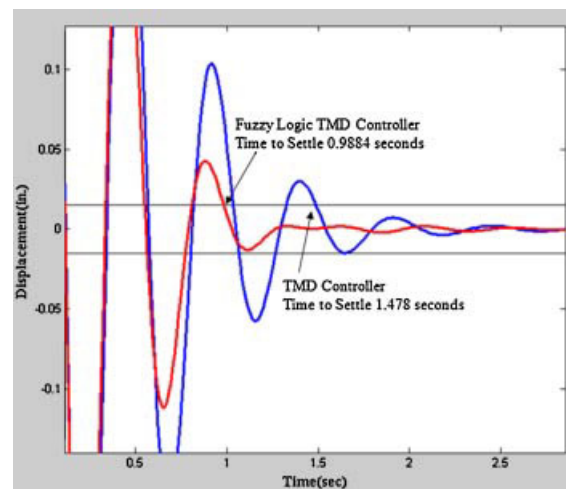


Figure 8 Time to settle within 3% for TMD and fuzzy TMD with structural mass of 1. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

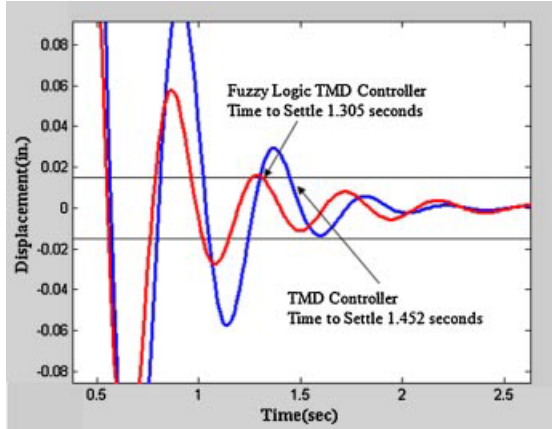


Figure 9 Time to settle within 3% for TMD and fuzzy TMD with structural mass of 1.1. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

well under the expected total floor mass the structure will experience during its usage, there may be variations, which is why the robustness issue is of importance.

In order to verify the robustness of the fuzzy logic controller, another simulation is done using MATLAB. The time to settle for each mass, 0.9, 1, and 1.1 units, is found for each TMD within 3% of its initial disturbance. The same m -files are used as in the previous simulations with the exception that the m_1 value of the structure is changed to the new mass of the structure and the m_1 value within the equations of motion is changed to 1 (the original mass of the structure), as shown below:

$$\begin{aligned} dx(1) &= x(2); \\ dx(2) &= ((k_2 * x(3) - (k_1 + k_2) * x(1) - (c_1 + c_2) * x(2) + c_2 * x(4)) / 1); \\ dx(3) &= x(4); \\ dx(4) &= ((k_2 * x(1) - k_2 * x(3) + c_2 * x(2) - c_2 * x(4)) / m_2); \end{aligned}$$

The structure is assumed to settle once its displacement comes below 3% of the initial displacement. The initial

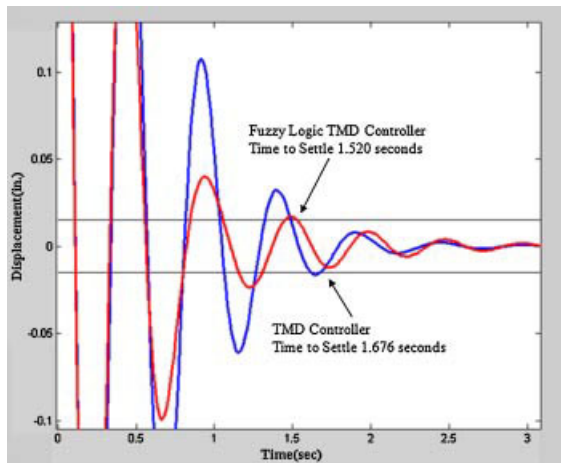


Figure 10 Time to settle within 3% for TMD and fuzzy TMD with structural mass of 0.9. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table II Robustness Test Results for Passive and Fuzzy TMD Time to Settle in Seconds Within 3%

Controller	m_1 value		
	1	1.1	0.9
Passive TMD (s)	1.648	1.770	1.421
Fuzzy logic TMD (s)	0.9884	1.245	0.927

disturbance is 0.5 in every simulation; 3% of this is 0.15 in. for displacement. The displacement response graphs of the each simulation are presented in Figures 8–10. The time taken to settle, in seconds, is presented in Table II.

After finding the time to settle under each mass, it can be concluded that the fuzzy logic TMD truly performed the best. The fuzzy logic TMD had a quicker settling time and lower amplitudes than the passive TMD for each cycle in each simulation. With these results, it can be concluded that the fuzzy logic TMD will perform better than a passive TMD even when the mass of the structure is slightly varied.

CONCLUSIONS

PD Controllers

Focusing more on applications being used today, PD controllers, which are active controllers, were used for further experimentation. The PD control consisted of two parameters, proportional (P) and derivative (D). By being able to modify these parameters individually, it was seen that the controller was most effective when both parameters are present compared to the case when just one parameter was present. However, it was also noted that when a P or D control is found for a specific earthquake it does not always perform as effective when subject to other earthquakes, leaving a slight flaw in the design.

MATLAB Simulations

Mathematical simulations of structures were carried out with the help of MATLAB. These simulations allowed the comparison between passive and semi-active controllers. The first simulation was conducted with a structure using only its inherent damping, found to usually be 5%. This was used as a base comparison to all other controllers. The passive controllers were implemented into the structure through MATLAB simulations. The plots of displacement and velocity of the structure vs. time were obtained from these simulations. The passive dampers considered, which are currently used, include the TMDs and base isolators. These dampers were shown to be more effective in both reducing the maximum displacement of the structure and also reducing the time it takes the structure to return to its equilibrium configuration.

Next, semi-active controllers were implemented into the structure where the damping coefficient of the TMD was varied. This variation of the damping coefficient was controlled by a fuzzy logic algorithm, which was created using the fuzzy logic toolbox in MATLAB. The fuzzy logic algorithm accounted for vagueness or fluctuation of certain parameters. In this research, it was found that a fuzzy logic controller produced better results

than a passive controller. Robustness tests were also conducted to confirm the effectiveness of a fuzzy logic controller. Taking into account for a 10% change in mass, the fuzzy logic based semi-active TMD controller still performed better than a passive TMD.

Recommendations

While conducting this research, a few ideas for future experimentation on the topic of earthquake resilient structures that could be implemented were arrived at. A great deal of the testing that was conducted during this research project was based on previous testing conducted during other research programs; however, there are still some improvements that can be made to achieve better and more useful results for future research programs. While testing during this REU summer program was done using one-story structures that had a scale of 1:24 the size of an actual structure, future research groups could explore how larger scale structures, such as 1:12, would perform during the experiments that were done. By testing at a scale closer to that of an actual structure, more knowledge can be gained on how an actual structure would perform to different frequencies and disturbances. While this might not be possible because of economic reasons, finding a way to show a parallel between small scale and larger scale testing would give a great deal of information towards the advancement of aseismic design. Using simulation based studies and actual tests, scaling factors could be developed to use small-scale model results to predict prototype behavior.

While at least one previous REU program has explored tests including single and multi-story structures, the time limitations within this program did not allow the multi-story tests to be performed. However, studying multi-story structures would have allowed for more hands-on understanding on the ideas of multiple degrees of freedom and a structure having multiple frequencies. While these ideas were studied through literature review and visual aids, data would have helped with further understanding on the subject.

One last experiment that is recommended for a future study involves further exploration into the use of PD controllers; specifically implementing fuzzy logic into PD controllers. Simulating an effective PD controller through MATLAB, as well as performing a simulation of a PD controller which uses fuzzy logic would give useful information into the effectiveness of fuzzy logic for another type of controller. After performing MATLAB simulations on PD controllers, a fuzzy logic based PD controller could be compared to a normal PD controller. If a fuzzy logic PD controller can be found to be more effective, it can be implemented into actual structures as a safer and more cost efficient way to make a structure more resilient to earthquakes.

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BIOGRAPHIES



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