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Article *in* Journal of Vibration and Control · September 2013

DOI: 10.1177/1077546312449034

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Review

JVC

Journal of Vibration and Control
19(12) 1763–1772

DOI: 10.1177/1077546312449034
jvc.sagepub.com
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Enhancement of a tuned mass damper for building structures using fuzzy logic

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Abstract

Over the past 10 years there has been a growing need to introduce closed-loop control technology for vibration suppression of buildings subject to wind or earthquake disturbances. This paper deals with the investigation of the effectiveness of a fuzzy logic based time variable damping tuned mass damper (TMD) on a building structure undergoing free and forced vibrations. The uniqueness of this approach is the application of a robust, nonlinear fuzzy based controller to emulate a time-optimal control strategy. Fuzzy logic based time variable damping is introduced into a semi-active TMD in order to enhance its performance in the vibration suppression of buildings. First, a single story structure for three different vibration suppression approaches is studied. The fuzzy logic based time variable damping TMD (fuzzy TMD) is compared to the baseline passive TMD as well as a conventional proportional-derivative (PD) controller. Forced vibration is introduced using a resonant harmonic sinusoidal excitation (i.e. same frequency as the fundamental frequency of the structure). Finally, the fuzzy TMD is compared to the baseline for the free vibration of a 15 story structure. For both structures studied, MATLAB® based simulation results show that the passive TMD and the PD, both constant gain approaches, provide similar results whereas the fuzzy TMD yields half the settling time. This effort clearly demonstrates the potential of a variable gain (damping) strategy for the vibration suppression of buildings.

Keywords

Fuzzy logic, semi-active control, tuned mass damper, vibration suppression of building structures

Received: 6 December 2010; accepted: 8 April 2012

1. Introduction

Vibration suppression of buildings has always been a concern for structural engineers, especially when it comes to tall buildings. Wind forces and earthquakes apply forces to the structure causing it to vibrate, which can cause damage to the building and inconvenience to people inside and even loss of life in the case of earthquakes (Inman, 1994; Connor, 2003). Vibration in buildings can be suppressed by introducing suppression and/or control devices. Control systems used in buildings counteract the abovementioned naturally occurring excitations and can be classified into four categories namely passive, active, hybrid, and semi-active controls based on whether they consume external power.

Passive suppression devices are those mechanisms which do not require external power for its operations. Base isolators and tuned mass dampers (TMD) come under this category. Active controllers are those devices which require external power for their operation. They use external power directly to apply counteracting force to the forces acting on the building. Hybrid controllers are a combination of both active and passive systems and either one or both of them together will function at a time depending on the nature and magnitude of the external excitation (Shiba K, Mase S, Yabe Y and Tamura K, 1998; Ahmadi G, 1995). Semi active controllers are a type of passive control which requires external power for operation. But unlike active control, it uses the external power to modify the parameters (gains) of

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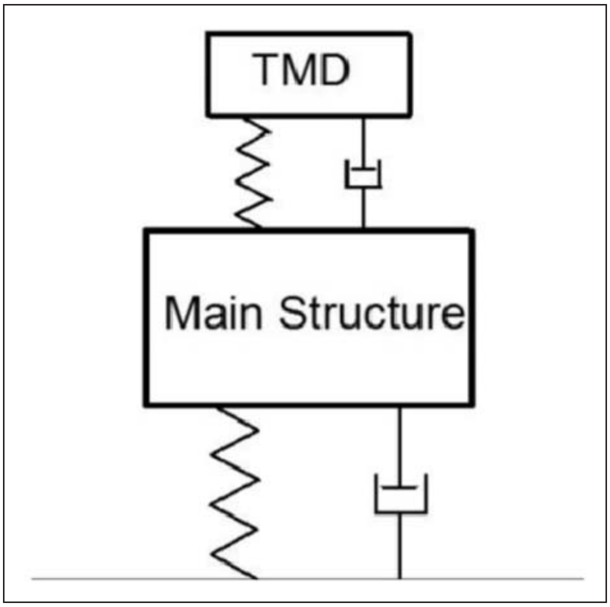

Figure 1. Schematic diagram of a tuned mass damper attached to the main structure.

the controller like its damping coefficient or stiffness. The semi-active control strategy consumes substantially lower amounts of power than that of the purely active control approach while performing significantly better than passive controllers. The fuzzy controller discussed in this paper is a type of semi-active control where external power is used to modify the damping coefficient of a TMD in order to enhance its performance.

A TMD consists of a mass, a spring and a damper and is attached to the structure as shown in Figure 1. The natural frequency of the TMD (which is based on its mass and stiffness) is tuned to the mass of the structure, so that when the structure moves in one direction, the TMD moves in the opposite direction providing a counteracting force in the direction opposite to the direction of motion of the structure, thereby bringing it to its stable position faster. Some recent researches have been done to enhance the performance of TMD by varying its damping coefficient and stiffness. However, the main modification in this research is that it introduces an approach which provides continuous tuning of damping coefficient by means of a fuzzy logic algorithm.

2. Objective of study

The main objective of this research is to enhance the performance of a TMD by means of semi-active methods using a fuzzy logic control algorithm. The development of the fuzzy controller (forming the membership functions and rule base) is done by performing tests on a one story structure which has the same fundamental frequency of the 15 story structure presented by Guclu and Yazici (2006). The developed controller is then tested on the modified 15 story structure of Guclu and Yazici (2006). The ground story stiffness and mass of the structure is significantly lower and this structure takes an impractically long time to settle down. The modification introduced in this effort to the 15 story model, thereby making the model more realistic, makes the stiffness and mass properties of the ground floor similar to other floors. All the simulations are run in MATLAB® and the fuzzy controller is developed using the fuzzy toolbox in MATLAB®. Additionally, the rationale behind the optimal strategy for developing a time variable damping coefficient for the fuzzy logic controller is mathematically determined and demonstrated.

3. Time variant damping

Juan and Phang (1991) observed some of the basic properties of a mass-spring-dashpot dynamic system like a TMD which are:

- When attached to any mechanical system, the damping of the system is almost always augmented regardless of the system size.
- The parameters are relatively model independent and thus insensitive to system uncertainties.
- No matter what happens, it will not destabilize the system since it is a energy dissipating device.

Thus, a damping device is a stable way to control a system irrespective of the uncertainties and complexities in the system. Further, Shahruz, Langari and Tomizuka (1991) showed that optimal damping strategy for a second order system that results in the minimum settling time is of bang-bang nature. To mathematically prove that the time optimal damping strategy of a one degree-of-freedom (d.f.) system is of bang-bang nature, let $u(t)$ be the control (damping ratio) that minimizes the performance index J which is given by

$$J = \int_0^{tf} dt \tag{1}$$

where t_f is the final time, i.e., the time at the which the body comes to rest.

The equation of motion of this one d.f. system is given by

$$m\ddot{x} + c\dot{x} + kx = 0 \tag{2}$$

where m is the mass, c is the damping coefficient and k is the stiffness of the system. In this illustrative example, the values of m and k are given (i.e. given natural frequency, ω [radians/sec]) and the control variable is the damping coefficient c. Let $x_1(t)$ and $x_2(t)$ be the displacement and velocity of the body at a given time t respectively. There follows the equation for ω and $u(t)$ as:

$$\omega = \sqrt{\frac{k}{m}} \quad u(t) = \frac{c}{2\sqrt{km}} \tag{3}$$

where $u(t)$ is the damping ratio which is the control parameter and a function of time.

The control equations can thus be written as

$$\dot{x}_1(t) = x_2(t) \tag{4}$$

Combining (3) and (4), gives

$$\dot{x}_2(t) = -2\omega u(t)x_2(t) - \omega^2 x_1(t) \tag{5}$$

The control $u(t)$ is constrained to $0 \leq u(t) \leq u_{max}$

In this study, it is assumed that $u_{max} = 1$. The Hamiltonian, H, developed in a similar manner as by Cohen et al. (2001) is given by

$$H = 1 + \lambda_1(t)x_2(t) - \lambda_2(t)[\omega^2 x_1(t) + 2\omega u(t)x_2(t)] \tag{6}$$

where λ is a co-state vector which has the same dimension as that of $x(t)$.

For the sake of convenience of calculation, substituting $\omega = 0.5$, reduces equation (6) to

$$H = 1 + \lambda_1(t)x_2(t) - \lambda_2(t)[0.25x_1(t) + u(t)x_2(t)] \tag{7}$$

The co-state equations are given by

$$\dot{\lambda}_1 = -\frac{\partial H}{\partial x_1} = \frac{\lambda_2(t)}{4} \tag{8}$$

$$\dot{\lambda}_2 = -\frac{\partial H}{\partial x_2} = -\lambda_1 + u\lambda_2(t) \tag{9}$$

$u(t)$ is a linear function of the Hamiltonian. So, the control $u(t)$ to minimize H is given by

$$u = 0 \text{ for } \lambda_2(t)x_2(t) \tag{10}$$

$$u = 1 \text{ for } \lambda_2(t)x_2(t) > 0 \tag{11}$$

Thus the control is of bang-bang nature. More details concerning the effectiveness using the bang-bang approach are presented by one of the co-authors of this current effort in Cohen et al. (2001). That is, the control $u(t)$ takes only its extreme values and switches between its maximum and minimum values at the switching points. There can be a maximum of only two switching points which will be either at $x_2(t) = 0$ or at $\lambda_2(t) = 0$.

This shows that time-variant damping strategy proves to be more effective than a time-invariant damping strategy. However, this strategy has not been implemented into complex and challenging systems due to some reasons such as (further details in Cohen et al., 2001):

- The lack of robustness in view of uncertainties in plant model and external noise.
- The uncertainty in the number of switch points which depends on the initial conditions.
- The implementation into a closed loop system is practically ineffective due to sensitivity to plant uncertainty.

The implementation of a time variable damping approach requires integration of control laws into the system with relative ease and simplicity while providing the required robustness. Fuzzy logic is used to make the control algorithm to achieve the desired control.

4. Fuzzy logic control

One of the gifts of nature is the inherent human capability of making effective decisions based on inexact linguistic information. This all-important characteristic has often led to the preference of man in the loop type control as opposed to autonomous controlled machines. Hence the performance of a controller dealing with uncertain systems can be improved by emulating human reasoning in its control algorithm. A logical system that attempts to capture the spirit of our approximate, imprecise world was introduced by Lotfi Zadeh as the theory of fuzzy sets, which in time has proved to be a very powerful tool for dealing quickly and efficiently with imprecision and nonlinearity (Cohen, 1999).

One of the inherent properties of fuzzy logic systems is that it has the capability of being a universal approximator (Cohen, 1999). Fuzzy logic is capable of approximating any continuous nonlinear function when sufficient number of inputs, rules and outputs are provided. This property of fuzzy logic has helped in improving the performance of many applications for lower costs by using fuzzy logic for its control algorithm (Kosko B and Isaka S, 1993; Thomas DE and Armstrong-Hélouvry B, 1995). The use of fuzzy logic control algorithm for time variant damping will help in approximating the bang-bang type of time optimal damping mechanism. Further, fuzzy logic algorithms can be modified and debugged a lot easier when compared to conventional methods.

From the solution for the time optimal damping strategy for a one d.f. system (which is of bang-bang nature), it can be observed that the system has its minimum damping coefficient when it is away from the equilibrium position, and as it comes back to its equilibrium position, the damping coefficient switches to its maximum value at the switching point. The fuzzy rules in the controller discussed in this paper have been modeled to mimic this action of the time optimal damping strategy. The rules of the fuzzy algorithm is set such that the damping coefficient of the TMD is low when the structure is away from its stable position so that the TMD will exert more force to bring the structure back to its stable position, and the damping coefficient of the TMD is high when the structure is close to its stable position so that the structure remains in its stable position.

5. Application to one story structure

5.1. Free vibration tests

The mass and stiffness of the one story structure was determined so that it would coincide with the same fundamental frequency as that of the 15 story structure studied later in this effort and based on Guclu and Yazici (2006). Thus, the mass and stiffness of the structure selected is

$$m = 1\,\text{kg}$$
$$k = 2.7479\,\text{N/m}$$

where m is the mass of the structure and k the stiffness.

Free vibration simulation experiments were conducted on this structure by giving an initial displacement of 0.1 m to the top of the structure and allowing it to vibrate freely. This way, the time taken for the structure to come to rest without any control is 65 seconds.

Next, tests were conducted on this structure to find the best possible passive TMD for this structure. The mass of the TMD is taken as 10% of the total mass of the structure.

For the TMD to deliver optimal performance, the frequency of the TMD should not be exactly same as that of the main structure, rather it should have a ratio as given by Den Hartog (1956) which is

$$R_{opt} = \frac{f_{TMD}}{f_{str}} = \frac{1}{1+\mu} < 1 \tag{12}$$

where,

R_{opt} = Optimum frequency ratio
f_{TMD} = Frequency of TMD
f_{str} = Frequency of structure, and
$\mu = \text{mass ratio} = \dfrac{mass\ of\ TMD}{mass\ of\ structure}$

from the above equation, the stiffness of TMD can be calculated to be

$$k_{TMD} = m_{TMD} \times \left(\frac{\omega_n}{1+\mu}\right)^2 \tag{13}$$

where,

k_{TMD} = stiffness of TMD
m_{TMD} = mass of TMD
ω_n = natural frequency of structure

To find the optimal damping coefficient of the TMD, a trial and error approach was implemented and the resulting damping coefficient was found out to be 0.0775 Ns/m. Thus the finalized TMD with a mass of 0.1 kg, damping coefficient of 0.0775 Ns/m and the stiffness as obtained from equation (2) was attached to the free end of the one d.f. structure.

A disturbance of 0.1 m was applied to the structure as an initial condition (transient excitation). The structural vibrations damped out using the passive TMD within 29 seconds as opposed to the 65 seconds for the primary structure (no TMD).

Next, a fuzzy control algorithm was developed to provide continuous modification of the damping coefficient of the TMD in order to enhance its performance. The rule base created for the fuzzy logic algorithm was based on the heuristic that the damping coefficient should have a small value when the error (difference between measured and desired displacement/velocity of the structure) is large and vice versa. The rule base created for the above fuzzy logic controller is given in Table 1. It is imperative to note that these heuristic rules are a direct outcome of the traditional optimal control solution obtained earlier which yields a bang-bang control strategy.

The inputs to the fuzzy control algorithm are the displacement and velocity of the structure and the output from the controller is the damping coefficient. The inputs to the fuzzy controller (displacement and velocity of the structure) are scaled in order to adapt to the range of the membership functions. The input and output membership functions develop for the fuzzy control algorithm are given in Figure 2. The surface

Table 1. Rule base for the fuzzy algorithm to determine the damping coefficient.

Displacement / Velocity	Negative high	Negative small	Zero	Positive small	Positive high
Negative	Small	Medium	Large	Medium	Small
Zero	Medium	Large	Extra large	Large	Medium
Positive	Small	Medium	Large	Medium	Small

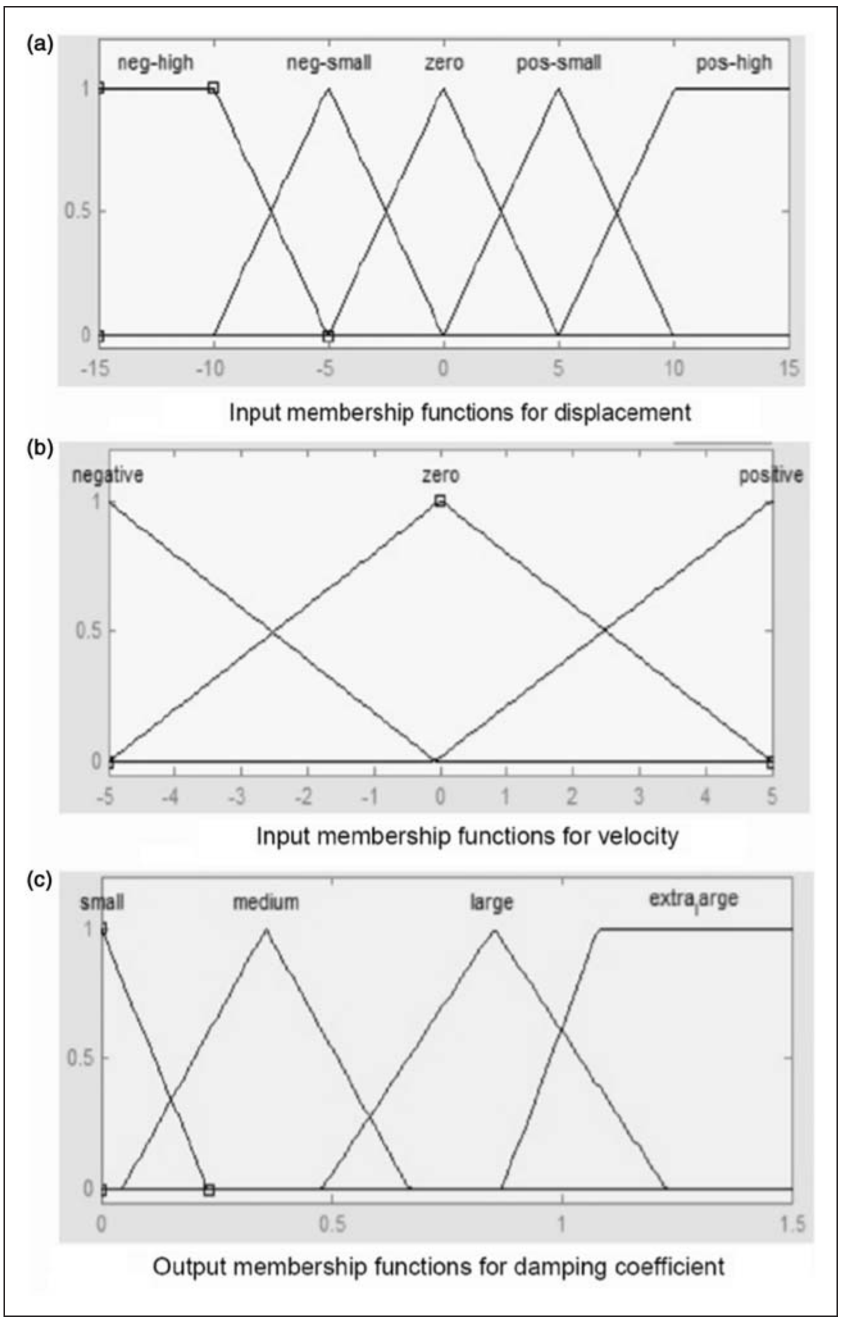

Figure 2. Fuzzy logic membership functions.

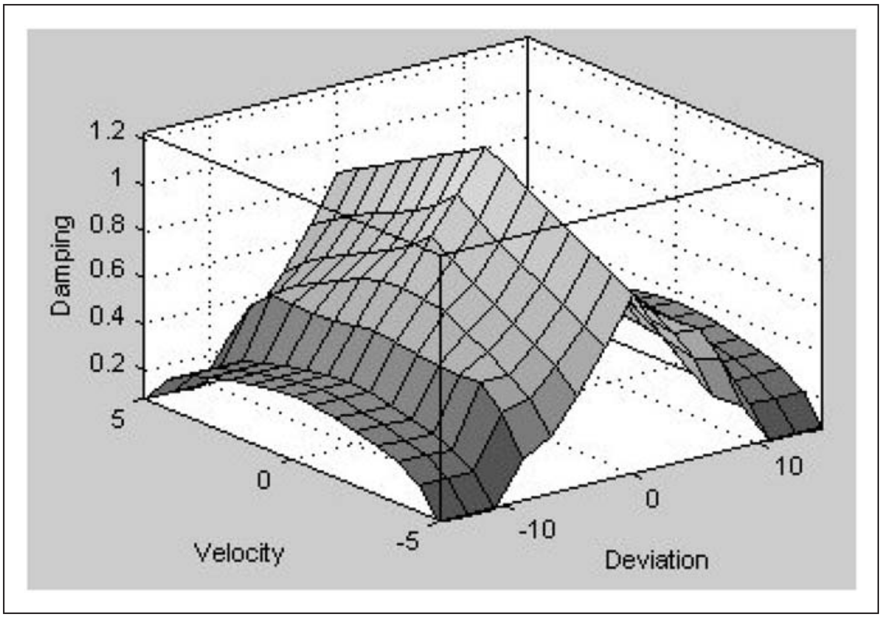

Figure 3. Fuzzy logic surface plot.

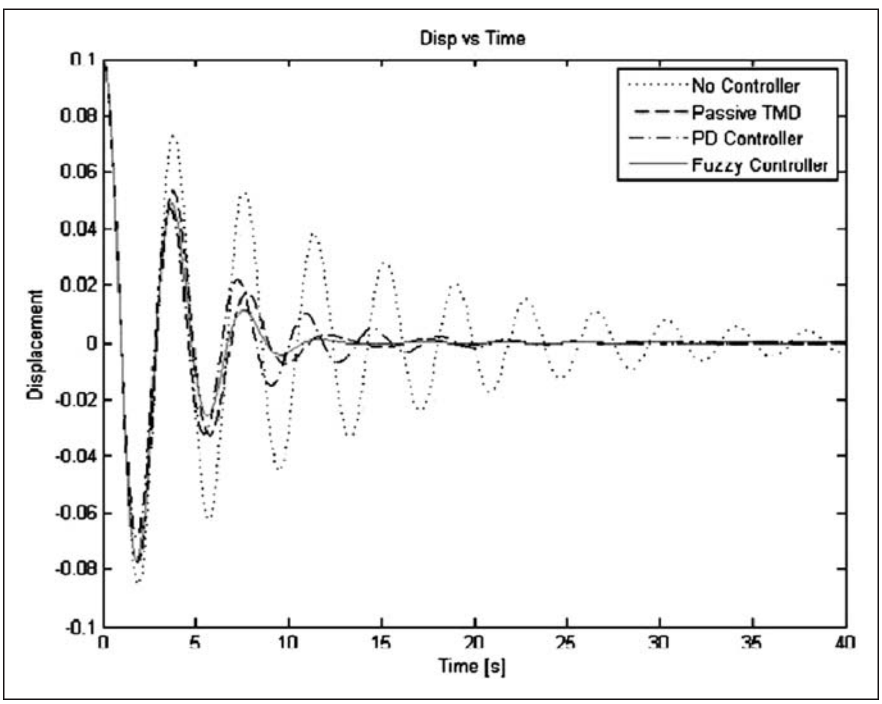

Figure 4. One story structure subject to initial displacement.

plot of the thus developed fuzzy controller is shown in Figure 3.

The output from the fuzzy controller (damping coefficient) was further multiplied by an optimum scaling factor (0.0875 - which was obtained by trial and error). This developed controller was then attached to the structure undergoing a similar free vibration test as described for the uncontrolled and passive TMD cases. The settling time obtained using the fuzzy controller is 14 seconds, which is less than half the time which resulted using the passive TMD, 29 sec.

Tests were also done with a proportional-derivative (PD) controller attached to the structure. The tuning of PD controller was done with the goal to achieve the

Table 2. Time taken to settle for an initial disturbance of 0.1 m

	Structure with no controller	Structure with passive TMD	Structure with PD controller	Structure with fuzzy TMD
Time taken to settle (in seconds)	65	29	30	14

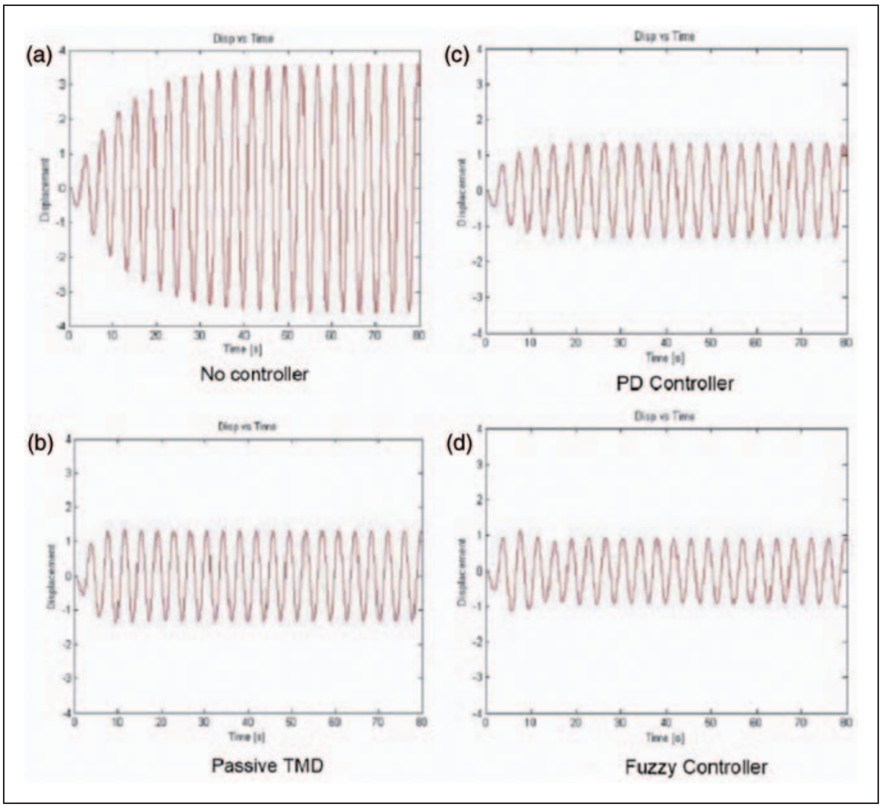

Figure 5. One story structure subject to forced harmonic vibration.

lowest settling time. A constraint was placed on the maximum allowable force so that "apples to apples" can be compared. The maximum force that the fuzzy TMD exerts on the structure during simulation was found out, and the proportional and derivative constants of PD controller was set such that the maximum force exerted by the PD controller on the structure does not exceed the maximum force exerted by the fuzzy TMD. From the various sets of values of these constants that met this constraint, the one that brought the structure to rest in the least amount of time was chosen to be the best PD controller. The PD controller was designed using trial and error methods. However, the gains are fixed whereas in the fuzzy controller these gains adapt to the 'situation of the state'. The adaptation policy is based on the emulation of a bang-bang strategy as detailed by Cohen et al. (2001). Figure 4 shows the displacement versus time graph for different control approaches.

Table 2 shows a summary of the time taken by the structure with and without different controllers to come to rest for a given initial disturbance of 0.1 m. It can be seen that the structure with fuzzy TMD is the most efficient strategy for control.

5.2. Forced vibration tests

The structure was excited with a sinusoidal wave with a frequency that matches the natural frequency of the structure so that the structure is in resonance. The displacement of the structure with and without the different controllers was observed. Figure 5 shows the displacement versus time graph of the structure with and without different controllers for forced vibration.

Table 3. Maximum displacement of the structure for sinusoidal excitation at resonance frequency

	Structure without any controller	Structure with passive TMD	Structure with PD controller	Structure with fuzzy TMD
Maximum displacement (in meters)	3.6172	1.3631	1.153	1.33

From the graphs shown in Figures 5(a) to (d), it can be observed that the amplitude of vibration is least when the fuzzy controller is attached to it. This further proves the effectiveness and superiority of the fuzzy controller over the passive and fixed gain active control (PD). From Figure 5(d) it can be observed that though the maximum displacement of the structure of 1.153 m occurs in the second cycle of vibration, the amplitude reduces to 0.92 m in the following cycles which is significantly lower than the maximum amplitude of displacement of the structure with other controllers installed on it. Table 3 summarizes the maximum displacement of the structure with and without different controllers for the sinusoidal excitation. The result shows that fuzzy TMD performs better than other controllers for the structure subjected to forced vibrations.

6. Application to 15 story structure

As mentioned before, the 15 story structure presented by Guclu and Yazici (2006) was used for testing with a modification in the structure that the mass, stiffness and damping coefficient of the ground floor was made identical to the other floors to obtain a reasonable structure.The mass, stiffness and damping coefficient of each floor used are 345600 kg, 340400000 N/m, and 2937000 Ns/m respectively. A schematic diagram of the 15 story structure with TMD attached to it is shown in Figure 6.

The TMD developed for this structure had a mass of 10% of the mass of the total structure. The stiffness of the TMD was found out using equation (2). The optimal damping coefficient for the TMD was found by trial and error. The fuzzy controller for this structure was developed using the same membership functions and rules as that of the fuzzy controller developed for the one story structure. Scaling factors for inputs were used here too just like in the one story structure case. The optimum scaling factor (962890) for the output from the fuzzy controller which gave the best performance for the controller was tuned using a trial and error method. The testing procedure for this structure is given as follows:

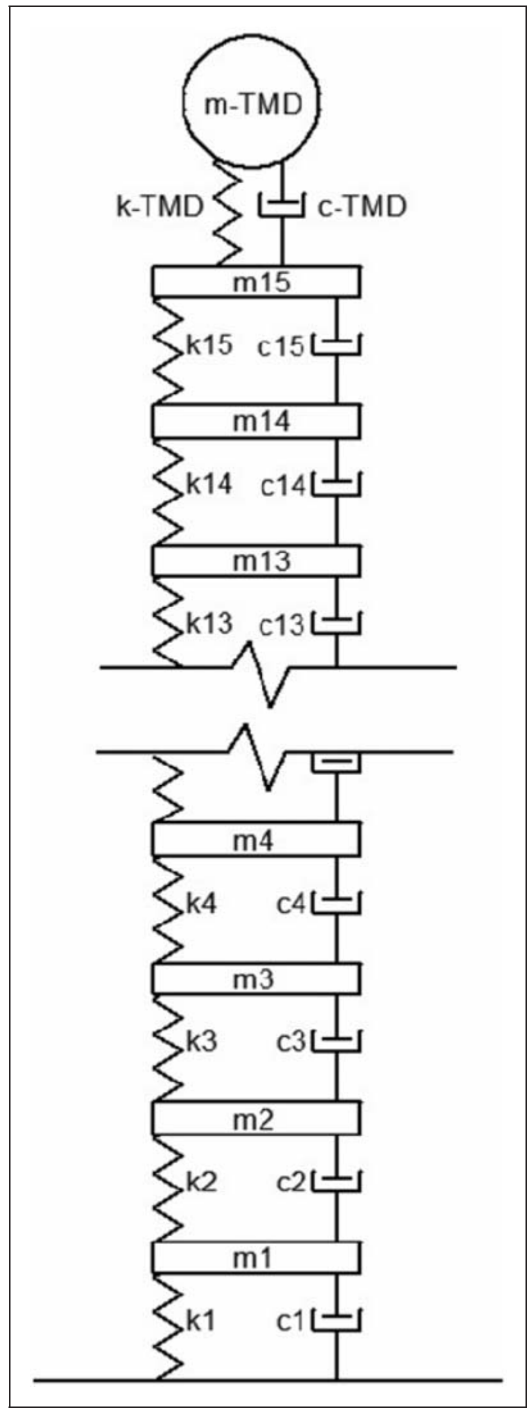

Figure 6. Schematic diagram of the 15 story structure with tuned mass damper attached to it.

- The top floor of the 15 story structure was given an initial displacement of 0.1 m without any controller

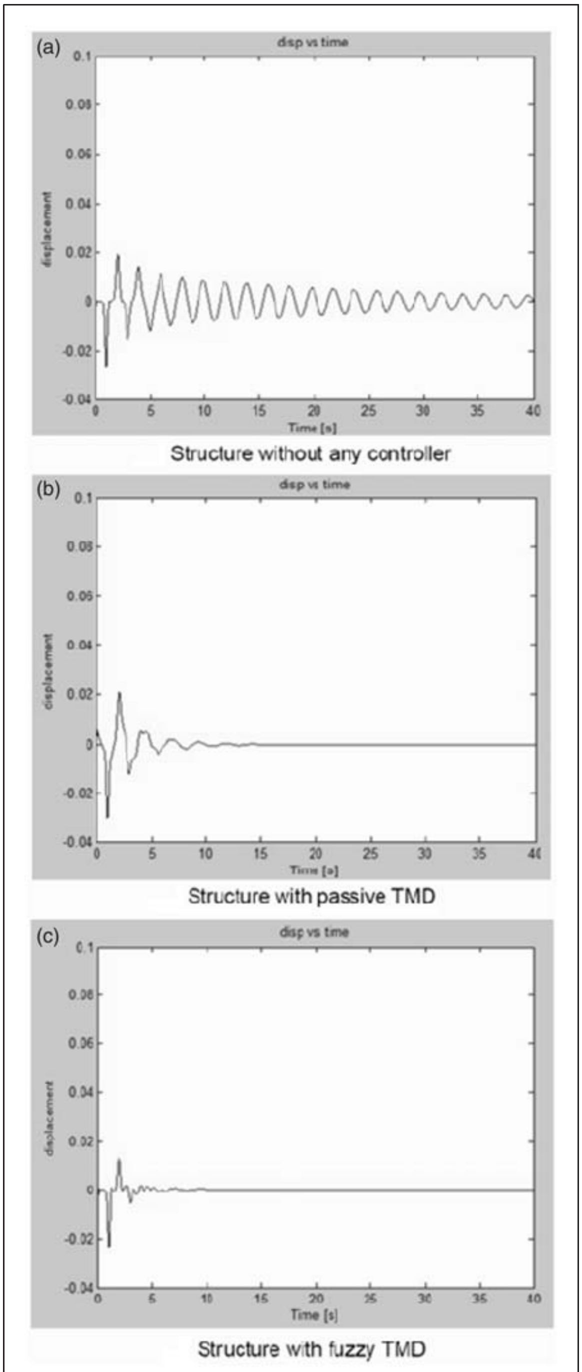

Figure 7. Time history of structural response for various control strategies.

attached to it and was allowed to vibrate freely and the settling time was observed.

- Then the passive TMD and the fuzzy logic controller were introduced and the above test repeated.

Figure 7 shows the displacement versus time graph of the structure with and without controllers.

Table 4 shows the time taken by the 15 story structure to come to rest for an initial displacement of 0.1 m with and without controllers. It can be clearly observed that the fuzzy controller brings the structure to rest in the least amount of time. This proves the effectiveness of the fuzzy controller for multi-story buildings involving vibrations in multiple modes too.

7. Conclusions

The present effort describes the MATLAB® based simulation testing of a semi-active TMD. Fuzzy logic is introduced to control the TMD's damping coefficient based on displacement/velocity measurements. The fuzzy logic algorithm mimics the time-optimal bang-bang control strategy. The controller was tested on a one story structure for free vibrations and the results were compared with the best possible passive TMD controller and the best possible PD controller. The controller was also tested on the same one story structure for forced vibrations and the results were again compared with the passive TMD controller and the PD controller. Results showed that the fuzzy TMD performed significantly better than both the passive TMD and PD controller for both free and forced vibrations.

The fuzzy controller was further tested on a 15 story structure to check and confirm its performance on a multi-story structure with multiple modes. Free vibration experiments were conducted on this structure with both the fuzzy TMD and passive TMD. The results again showed that the fuzzy TMD performed better than the passive TMD. This test confirmed the effectiveness of fuzzy TMD for structure with multiple stories and modes.

Table 4. Time taken to settle for a given initial displacement of 0.1 m

	Structure without any controller	Structure with passive TMD	Structure with fuzzy TMD
Time taken to settle (in seconds)	110	15	9

8. Recommendations

1. Current research involved only the study of the performance of fuzzy TMD on structures for free and forced harmonic vibrations. Further research may include studying the performance of fuzzy TMD for a structure subject to seismic disturbances.
2. Genetic algorithms can be developed which will automatically tune the membership functions of the fuzzy controller to provide minimum settling times.
3. This developed controller can be tested on other civil engineering structures like bridges, transmission towers, large latticed truss structures etc.

These efforts are being pursued and findings will be reported in subsequent publications.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

Ahmadi G (1995) Overview of base isolation, passive and active vibration control strategies for a seismic design of structures. *Scientia Iranica* 2(2): 99–116.

Cohen K (1999) Active and passive control of flexible structures. PhD Thesis, Technion IIT, Haifa, Israel.

Cohen K, Weller T and Asher JZB (2001) Control of linear second-order systems by fuzzy logic-based algorithm. *Journal of Guidance, Control, and Dynamics* 24(3): 494–501.

Connor JJ (2003) *Introduction to Structural Motion Control*. Upper Saddle River, NJ: Prentice Hall.

Den Hartog JP (1956) *Mechanical Vibrations*. New York: McGraw Hill.

Guclu R and Yazici H (2006) Fuzzy logic control of a non-linear structural system against earthquake induced vibration. *Journal of Vibration and Control* 13(11): 1535–1551.

Inman DJ (1994) *Engineering Vibration*. Upper Saddle River, NJ: Prentice Hall.

Jaung JN and Phan M (1991) Robust controller designs for second-order dynamic systems: a virtual passive approach. *AIAA Paper* AIAA-91-0983-CP: 1796–1805.

Kosko B and Isaka S (1993) Fuzzy logic. *Scientific American* 269(1): 76–81.

Shahruz SM, Langari G and Tomizuka M (1991) Optimal damping ratio for linear second-order systems. In: *Proceedings of the 30th Conference on Decision and Control*, Brighton, England, Dec. 11–13. pp. 2324–2325.

Shiba K, Mase S, Yabe Y and Tamura K (1998) Active/passive vibration control systems for tall buildings. *Smart Materials and Structures* 7(5): 588–598.

Thomas DE and Armstrong-Hélouvry B (1995) Fuzzy logic control – a taxonomy of demonstrated benefits. In *Proceedings of the IEEE* 83(3): 407–421.