Semi-Active Fuzzy Control of Tuned Mass Damper to Reduce Base-Isolated Building Response under Harmonic Excitation

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ABSTRACT

In this paper, a closed loop control approach for controlling vibration under harmonic excitation is introduced. A Semi-Active Tuned Mass Damper (SATMD) with time variable damping installed on the lowest floor of a base-isolated structure is investigated. The damping is controlled by a fuzzy logic controller, in which displacement and velocity of the base isolator are used as inputs.

The numerical simulation is carried out on two types of 6-degrees of freedom base-isolated structures: the first structure is equipped with a base isolator having low damping, while the second structure is equipped with a base isolator having high damping. Simulation by MATLAB is carried out to test the proposed SATMD under harmonic excitation and the results are compared to those of a classical passive TMD. Results showed that a SATMD with variable damping is more efficient than a classic TMD with constant damping under harmonic excitation, leading to a reduction of 50% in base displacement and acceleration, as well as a reduction of nearly 15% in inter-story drift.

KEYWORDS: Semi-active tuned mass damper (SATMD), Variable damping, Fuzzy logic controller, Base-isolated building, Harmonic excitation, Vibration control.

INTRODUCTION

Civil engineering safety and structural integrity are of highest importance, as the consequences of failure are devastating. Maintaining structural integrity becomes particularly important when structures are subjected to violent earthquakes, as already experienced during the 1994 Northridge, USA, the 1995 Kobe, Japan and the 1999 Kocaeli, Turkey earthquakes. Such earthquakes can bring structures to critical conditions, resulting in large displacement, high velocity and acceleration.

To date, many control systems have been mounted on structures to protect structures against earthquakes. According to the principle of operation, those control systems can be classified into three general categories: passive control systems, active control systems and semi-active control systems (Ahmadi, 1995).

Passive control systems are designed to absorb and dissipate energy; this type of system does not require an external source of energy or any control algorithm. Tuned Mass Damper (TMD) is one of passive control...
devices proposed for flexible structures mostly resisting wind vibrations. Contrary to passive systems, active control systems are able to oppose dangerous loads in a controlled manner by producing appropriate reaction forces on the structure. The intensity and variation of the control force are supervised by a controller complicating the control strategy while having the risk of instability due to time delay. Active control systems are suitable for high-rise buildings. Semi-active control is a sort of adaptive passive system which requires no huge external source of energy; on the contrary, small energy might be used to modify parameters of the control system, changing damping or stiffness.

Seismic isolation is one of the first proposed passive control systems installed between the foundation and the superstructure. Base isolators need to have very large horizontal flexibility and very high vertical stiffness. These devices are able to uncouple the movement of the structure of the ground in order to reduce the forces transmitted to the superstructure. Laminated rubber bearings are widely used as base isolation system (Kelly, 1993).

Semi-active approach consists of incorporating devices within the structure whose properties can be adjusted in real time during earthquakes, improving system performance control. Semi-active devices have the advantage of low energy consumption. Such devices can be magneto-rheological (MR) dampers, variable stiffness devices, variable friction devices or variable orifice fluid dampers whose property changes during real time. Yang et al. (2000) proposed a new resetting semi-active stiffness damper (RSASD). The performance of the proposed RSASD was investigated using two models; the first one was a three-story scaled building and the second one was an eight-story full-scale building. Agrawal and Yang (2000) proposed a Semi-Active Electromagnetic Friction Damper (SAEMFD), where the friction force between two sliding plates is regulated by controlling the normal force using an electromagnetic field. The proposed SAEMFD was mounted on a base-isolated building. Cao and Li (2004) used an active TMD to examine the performance of new control strategies. The TMD was proposed based on response parameter analysis, considering the Nanjing TV tower in the simulation.

Kumar et al. (2007) used the linear-quadratic optimal control algorithm to design an active control system for buildings against earthquake excitations. A single degree of freedom building was used to illustrate the effect of an active TMD leading to 35% more reduction in vibration of the structure than when considering passive control.


Aldawod et al. (2001) studied the effect of applying a control force to a 306 m tall benchmark office tower for the city of Melbourne, Australia. The control force was generated by means of an active TMD using a fuzzy logic controller. The effectiveness of the proposed damping system is tested under long wind excitation. Pourzeynali et al. (2007) used a combined application of genetic algorithms and fuzzy logic controller to reduce vibration of an 11-story 2D building frame subjected to different earthquake records.

Combining two control systems can be more effective, so that some failures noted for specific control systems, like large lateral displacement in the case of lead rubber bearing base isolation system due to low stiffness, can be avoided (Tavakoli et al., 2014). The same controller used by Pourzeynali et al. (2007) was later used to control pounding between buildings (Abdeddaim et al., 2016a, b).

To reduce base isolator displacement, many mechanisms can be used by either active or semi-active devices. Palazzo and Petti (1996) applied a TMD on a base-isolated system subjected to random excitations.
Tsai (1995) and Djedoui and Ounis (2016) studied the effect of a TMD on the seismic response of a base-isolated building. The building under consideration was a 2D shear frame with six stories including basement. Djedoui et al. (2016) and Djedoui et al. (2017) showed the effectiveness of a hybrid system combining a base isolation with a passive and active TMD controlled by means of a PID and LQR controller.

Nazarimofrad and Zahrai (2017) presented a mathematical model to obtain the seismic performance of an irregular multi-story building with two ATMDs at center of mass on the top floor. The model was employed to investigate the seismic response of 10- and 15-story asymmetric plan buildings in different cases using fuzzy logic and LQR forces for those two ATMDs. Bathaei et al. (2017) investigated the performance of a SATMD with adaptive MR damper using fuzzy controllers of type-1 and type-2 for seismic vibration mitigation of an 11-DOF building model. The TMD was installed on the roof and the MR damper was located on the eleventh story. The seismic performance of semi-active controller of type-2 considering the uncertainties related to input variables was higher than that of fuzzy controller of type-1. Ramezani et al. (2017) designed fuzzy systems for optimal parameters of TMDs to reduce seismic response of tall buildings. They proposed a method with regard to nonlinear decision-making of fuzzy systems and their sufficient ability to cope with different unreliability.

The main purpose of this paper is to study the effect of a fuzzy logic semi-active control of a TMD to reduce base displacement of a base-isolated structure for which six degrees of freedom structural system is simulated. The structural system is the same used by Tsai (1995). The fuzzy logic controller is designed to reduce base isolator displacement by changing the damping of the TMD. Simulations are conducted under harmonic excitation.

**Control Theory**

TMD is a mass with constant stiffness and damping coefficients attached to a primary system to reduce undesirable vibrations. Changing the parameters (stiffness and/or damping) of the TMD continuously may enhance the performance of the TMD (Pinkaew and Fujino, 2001).

As previously mentioned, the proposed SATMD provides a variation of the damping of the TMD using a fuzzy logic controller. Some recent research projects have been conducted to enhance the performance of a TMD by varying its damping coefficient and stiffness. Shahruz et al. (1992) showed the bang-bang nature and determined the optimal damping ratio for linear second-order systems. Edalath et al. (2013) found that a single degree of freedom (SDOF) system has its minimum damping coefficient when it is away from the equilibrium position; however, a maximum value of damping is needed to bring the system to its equilibrium position.

Based on this theory, a fuzzy logic controller designed by Zahrai et al. (2013) is used, where fuzzy logic rules are designed to control the damping of the proposed SATMD. The basis of forming these rules is in such a way that if displacement and velocity have the same sign, then the velocity of the structure is increasing and therefore high damping force is needed. On the contrary, if displacement and velocity do not have the same sign, it may be concluded that the structure is returning to equilibrium state and a very small damping force is required. On the other hand, if the input values are low, it can be concluded that a small damping force is required and vice versa (Zahrai et al., 2013).

**Multi Degrees of Freedom Model**

A base-isolated structure can be simplified as a SDOF; however in this study, a 6-story base-isolated lumped structure with an elastic behavior presented by Tsai (1995) as shown in Fig. 1 is used for applying a semi-active controlled tuned mass damper with variable damping. Only horizontal degrees of freedom are considered. The base of isolated structure is assumed as rigid mass $m_b$ and its displacement relative to the ground is denoted as $u_b$. The isolation system has lateral stiffness $k_d$ and damping $c_d$. The displacement of the
tuned mass-damper relative to the base is denoted as $u_b$. The superstructure has 5 degrees of freedom; each degree of freedom has a lumped mass $m_i$. The corresponding displacement component, $u_i$, represents the super-structural deformation relative to the base, while $v_i$ for $i = 1 \ldots n = 1$ denotes the relative displacement between two consecutive floors, e.g. $v_i$ is the relative displacement between $m_b$ and $m_i$. The total mass is:

$$m_f = m_b + \sum_{i=1}^{5} m_i$$

The response of this base-isolated building excited by ground acceleration $\ddot{u}_g$ can be written as:

$$m_f \dddot{u}_b + m_d \ddot{u}_d + \sum_{i=1}^{5} m_i \dddot{u}_i + c_b \ddot{u}_b + k_b u_b = -(m_f + m_d) \ddot{u}_g$$

(2)

$$m_i \dddot{u}_b + m_d \ddot{u}_d + c_d(t) \dot{u}_d + k_d u_d = -m_d \ddot{u}_g$$

(3)

$$m_i \dddot{u}_b + m_i \dddot{u}_i + \sum_{j=1}^{5} c_i \dddot{u}_j + \sum_{j=1}^{5} k_i u_j = -m_d \ddot{u}_g$$

(4)

For $i = 1 \ldots n$ and $j = 1 \ldots n$, $c_i$ and $k_i$ are the entries of the damping and stiffness matrices, respectively, of the superstructure without TMD installed on the structure.

The matrices $M$, $C$, and $K$ are given as follows:

$$M = \begin{bmatrix}
      m_b + \sum_{i=1}^{5} m_i & m_1 & m_2 & m_3 & m_4 & m_5 \\
      m_1 & m_1 & 0 & 0 & 0 & 0 \\
      m_2 & 0 & m_2 & 0 & 0 & 0 \\
      m_3 & 0 & 0 & m_3 & 0 & 0 \\
      m_4 & 0 & 0 & 0 & m_4 & 0 \\
      m_5 & 0 & 0 & 0 & 0 & m_5
\end{bmatrix}$$

(5)

$$C = \begin{bmatrix}
      c_b & 0 & 0 & 0 & 0 & 0 \\
      0 & c_1 + c_2 & -c_2 & 0 & 0 & 0 \\
      0 & -c_2 & c_2 + c_3 & -c_3 & 0 & 0 \\
      0 & 0 & -c_3 & c_3 + c_4 & -c_4 & 0 \\
      0 & 0 & 0 & -c_4 & c_4 + c_5 & -c_5 \\
      0 & 0 & 0 & 0 & -c_5 & c_5
\end{bmatrix}$$

$$K = \begin{bmatrix}
      k_b & 0 & 0 & 0 & 0 & 0 \\
      0 & k_1 + k_2 & -k_2 & 0 & 0 & 0 \\
      0 & -k_2 & k_2 + k_3 & -k_3 & 0 & 0 \\
      0 & 0 & -k_3 & k_3 + k_4 & -k_4 & 0 \\
      0 & 0 & 0 & -k_4 & k_4 + k_5 & -k_5 \\
      0 & 0 & 0 & 0 & -k_5 & k_5
\end{bmatrix}$$
The aim of this study is to apply fuzzy logic control to the damping of the SATMD. Fuzzy logic, introduced by Zadeh (1965), enables the use of linguistic directions as a basis for control, making real-time decisions pertinent to the control problem, which is a real challenge. However, Fuzzy Logic Controller (FLC) is very robust and capable of handling nonlinear systems. On the other hand, an FLC is fast enough to react in time. Expert knowledge is usually required to construct fuzzy logic controllers. A fuzzy logic controller is incorporated into a closed-loop control system similar to conventional controllers, as shown in Fig. 2.

The most widely used fuzzy control inference $R_i$ is the "if–then" rule, which can be written as follows when two input data are used in their antecedent parts (Wang, 1994):

$R: \text{if } x_1 = A_i \text{ and } x_2 = B_i \text{ then } y = C_i .$

Typically, a fuzzy logic controller is composed of four sections (Guclu and Yazici, 2007):
- The fuzzification interface to scale and map the measured variables into suitable linguistic variables (fuzzifier).
- A knowledge base comprising linguistic control rule base.
- A decision-making logic to infer the fuzzy logic control action based on the measured variables, which resembles human decision making (fuzzy reasoning engine).
- A defuzzification interface to scale and map the linguistic control actions inferred to yield a non-fuzzy control input to the plant being controlled (defuzzifier).
In this paper, a fuzzy logic algorithm proposed by Zahrai et al. (2013) is used. This algorithm is developed to provide continuous modification of the damping coefficient of the semi-active TMD. Linguistic variables, such as small, medium and big, are used to represent the domain knowledge, with their membership values varying between 0 and 1.

The inputs to the fuzzy control algorithm are the displacement and velocity of base structure, while the output from the controller is the damping coefficient. The inputs to the fuzzy controller (displacement and velocity of base structure) are scaled in order to adapt to the range of the membership functions. Table 1 illustrates fuzzy variables used in this FLC.

The input and output membership functions developed for the fuzzy control algorithm are given in Fig. 3. The proposed fuzzy controller has 24 if-then rules, built as shown in Table 2 and the surface of this controller is shown in Fig. 4.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>LP</td>
<td>Large positive</td>
</tr>
<tr>
<td>MP</td>
<td>Medium positive</td>
</tr>
<tr>
<td>SM</td>
<td>Small positive</td>
</tr>
<tr>
<td>SN</td>
<td>Small negative</td>
</tr>
<tr>
<td>MN</td>
<td>Medium negative</td>
</tr>
<tr>
<td>LN</td>
<td>Large negative</td>
</tr>
<tr>
<td>P</td>
<td>Positive</td>
</tr>
<tr>
<td>ZP</td>
<td>Small positive</td>
</tr>
<tr>
<td>ZN</td>
<td>Small negative</td>
</tr>
<tr>
<td>N</td>
<td>Negative</td>
</tr>
<tr>
<td>VS</td>
<td>Very small</td>
</tr>
<tr>
<td>S</td>
<td>Small</td>
</tr>
<tr>
<td>M</td>
<td>Medium</td>
</tr>
<tr>
<td>L</td>
<td>Large</td>
</tr>
<tr>
<td>VL</td>
<td>Very large</td>
</tr>
<tr>
<td>EL</td>
<td>Extremely large</td>
</tr>
</tbody>
</table>
Table 2. Rule base for the fuzzy logic controller

<table>
<thead>
<tr>
<th>Velocity</th>
<th>LN</th>
<th>MN</th>
<th>SN</th>
<th>SP</th>
<th>MP</th>
<th>LP</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>EL</td>
<td>VL</td>
<td>L</td>
<td>VS</td>
<td>S</td>
<td>M</td>
</tr>
<tr>
<td>ZN</td>
<td>VL</td>
<td>L</td>
<td>M</td>
<td>VS</td>
<td>S</td>
<td>M</td>
</tr>
<tr>
<td>ZP</td>
<td>M</td>
<td>S</td>
<td>VS</td>
<td>M</td>
<td>L</td>
<td>VL</td>
</tr>
<tr>
<td>P</td>
<td>M</td>
<td>S</td>
<td>VS</td>
<td>L</td>
<td>VL</td>
<td>EL</td>
</tr>
</tbody>
</table>

Figure (3): Membership functions of a) input displacement; b) input velocity; c) output damping coefficient
Simulation Procedure

In this study, MATLAB SIMULINK with fuzzy toolbox is used to determinate the performance of the controlled TMD; the 6- story structure presented by Tsai (1995) is used for testing the performance of the proposed SATMD. The base-isolated structure can be simplified as a six-degree of freedom system. Each floor has the same mass of 3500 kg, the same stiffness of 35 kN/mm and the same damping of 35 N.S/mm. The total mass of the base-isolated structure \( m_f = 21000 \) kg.

The numerical simulation is carried out on two types of isolation systems which have the same stiffness but different damping. The stiffness of the isolation system is \( k_b = 0.21 \) kN/mm, the first system isolation has a lower damping level \( c_b = 2.66 \) N.S/mm (structure A). The other type has a higher damping level \( c_b = 6.64 \) N.S/mm (structure B). The natural frequency of the base-isolated structures A and B is:

\[
\omega_b = \sqrt{\frac{k_b}{m_f}} = 3.15 \text{ rad/s} = 0.503 \text{Hz}
\]  

Parameters of the TMD are chosen to respect for minimum displacement response of the primary structure (Den Hartog, 1956).

\[
\omega_d = \frac{\omega_b}{1 + \mu}
\]  

where \( \omega_b \) denotes the natural radial frequency of the primary structure and \( \mu \) is the selected mass ratio

\[
\mu = \frac{m_f}{m_f} = \frac{m_f}{m_f}
\]  

and the damping ratio \( \xi_b \) and viscous damping coefficient \( c_b \) become:

\[
\xi_b = \frac{3\mu}{8(1 + \mu)^2}
\]  

\[
c_b = 2\xi_b m_f \omega_s
\]  

The ratio \( \mu \) is selected to be equal to 0.05; parameters of the chosen TMD are represented in Table 3.
Table 3. Parameters of the TMD

<table>
<thead>
<tr>
<th>Mass ratio $\mu$</th>
<th>Mass of TMD $m_d$</th>
<th>Stiffness $k_d$</th>
<th>Damping $c_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>1050 kg</td>
<td>9523.8 N/m</td>
<td>845.15 N.S/m</td>
</tr>
</tbody>
</table>

The value of damping, $c_d$, is used as output for the semi-active TMD.

In order to compare the effectiveness of the proposed semi-active TMD in reducing base displacement, acceleration and inter-story drifts of the base-isolated structure, both structures A and B are excited with a sinusoidal wave with a frequency that matches the natural frequency of the structures, so that the structures are in resonance.

Results and Performance of the Semi-active TMD under Harmonic Excitation

As mentioned before, the effectiveness of the proposed SATMD is tested; the simulation analysis of the 6-story buildings A and B with an SATMD installed on the lowest floor is conducted against harmonic excitation. Fuzzy logic controller uses base displacement and velocity as inputs while the output is the damping coefficient ranging from 0 to 845.15 N.S/m.

Since structural safety and comfort are dependent upon the maximum displacement and acceleration of floors, the response results of non-controlled base-isolated structures A and B, as well as base-isolated structures A and B equipped with the proposed TMD, are compared to those of the same structures equipped with a classic TMD having a constant damping.

The base displacement associated with the response reduction for the proposed control system along with the uncontrolled response subjected to harmonic excitation are presented in Fig. 5 for structure A and in Fig. 6 for structure B, respectively.

Controlling the damping of the SATMD accurately provides flexibility of the mass damper and results in a better dynamic equilibrium than that of a classical TMD.

As can be observed from the results shown in Figs. 5 and 6, the reduction ratio (ratio of control with classic TMD to control with the proposed SATMD) of the base isolation displacement is about 50%. Furthermore, the proposed SATMD reduces the base isolator acceleration by about 50% compared to that of a classic TMD for the same harmonic excitation, as shown in Fig. 7 and Fig. 8.

When using the SATMD with variable damping, maximum efficiency is achieved after a couple of cycles of vibration. Like in the classical TMD, the SATMD needs the energy stored from the primary structure to suppress the undesired vibration of the structure.

The proposed SATMD achieves maximum efficiency within 9 seconds. On the other hand, it can be observed, from Figs. 9 and 10, that the damping deployed for obtaining the above reductions in the controlled SATMD is about 25% of the total damping in the case of TMD with constant damping.

The effectiveness of the controlled TMD in reducing the response of the modeled building is also represented in inter-story drift quantities. Table 4 shows the maximum inter-story drift under the imposed harmonic excitation. It is observed from Table 4 that nearly 15% reduction in inter-story drift is achieved by means of a SATMD with variable damping.

Consequently, the results obtained demonstrate that the proposed SATMD is more effective than a classical TMD under harmonic excitation. The reduction in base isolator displacement may be reflected in a reduction in the dimensions of the base isolator.

Table 4. Maximum inter-story drift response in mm

<table>
<thead>
<tr>
<th>Structure</th>
<th>V1</th>
<th>V2</th>
<th>V3</th>
<th>V4</th>
<th>V5</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Classic TMD</td>
<td>0.2092</td>
<td>0.1575</td>
<td>0.1566</td>
<td>0.1046</td>
<td>0.0523</td>
</tr>
<tr>
<td>SATMD</td>
<td>0.1732</td>
<td>0.1308</td>
<td>0.1284</td>
<td>0.0857</td>
<td>0.0428</td>
</tr>
<tr>
<td>B Classic TMD</td>
<td>0.1647</td>
<td>0.1242</td>
<td>0.1228</td>
<td>0.0819</td>
<td>0.0410</td>
</tr>
<tr>
<td>SATMD</td>
<td>0.1457</td>
<td>0.1103</td>
<td>0.1072</td>
<td>0.0716</td>
<td>0.0358</td>
</tr>
</tbody>
</table>
Figure (5): Base displacement versus time for structure A

Figure (6): Base displacement versus time for structure B
Figure (7): Base acceleration versus time for structure A

Figure (8): Base acceleration versus time for structure B
Figure (9): Deployed damping (structure A)

Figure (10): Deployed damping (structure B)
CONCLUSION

This paper investigated the performance of a non-conventional TMD system with a time varying damper installed on base-isolated structures. The control of damping in the proposed SATMD is achieved by means of a fuzzy logic controller, in which base displacement and velocity are used as inputs.

Controlling damping in an adequate manner in the SATMD provides compatibility of the mass damper. A 2D simulation on MATLAB was carried out for two 6-degree of freedom base-isolated structures; the first structure is equipped with a base isolator having a low damping coefficient, while the second one is equipped with a base isolator having a high damping coefficient. Harmonic excitations at structural resonance condition were imposed to the structures.

The performance of the proposed SATMD results in decreasing base displacement and acceleration by about 50% and inter-story drifts by nearly 15%. The deployed damping in the case of the SATMD is less than those in conventional passive TMDs.

Finally, more research is required on the performance of SATMD for base-isolated structures against earthquake excitation. Further, this proposed SATMD can be used in other civil engineering structures, like bridges.

REFERENCES


