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Vibration control of a structure with ATMD against earthquake using fuzzy logic controllers

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Abstract

In this paper, fuzzy logic and PD controllers are designed for a multi-degree-of freedom structure with active tuned mass damper (ATMD) to suppress earthquake-induced vibrations. Fuzzy logic controller (FLC) is preferred because of its robust character, superior performance and heuristic knowledge use effectively and easily in active control. A fifteen-degree-of-freedom structural system is modeled with two types of actuators. These actuators are installed on the first storey and fifteenth storey which has ATMD. The system is then subjected to Kocaeli Earthquake vibrations, which are treated as disturbances. In control, linear motors are used as the active isolators. At the end of the study, the time history of the storey displacements and accelerations, ATMD displacements, control voltages, frequency responses of the both uncontrolled and the controlled structures are presented. Performance of the designed FLC has been shown for the different loads and disturbances using ground motion of the Kobe Earthquake. The results of the simulations show a good performance by the fuzzy logic controllers for different loads and the earthquakes.

1. Introduction

A high-rise building has been categorized as a multi-degree-of-freedom structure and research findings and practical applications show that structural control can protect these types of structures from damage caused by earthquakes, strong winds or other natural hazards. Proposed techniques to minimize the structural vibrations, in general, consist of two categories, namely passive control systems and active control systems [1]. Passive systems add damping to the structure or isolate it from the source of environmental excitation, thus reduce vibration. These systems have been widely used because of their simple mechanism, reliability and low cost. However, their control capacity is limited. In the actively controlled system, control forces are generated using an external energy source and applied to the structure through actuators according to a prescribed control algorithm. Active systems have the advantage of strong capacity. Active devices can be designed to

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influence a number of vibration modes. Hence, active control is most suited for a multi-degree-of-freedom structure, whose response can be influenced by a number of natural modes. The effects of the active control are obviously superior to the passive control in decreasing the response of structure vibration. Alternatively, passive control may be added to an active control scheme to decrease its energy requirements. However, due to increase in flexibility and height of buildings, the importance of the active control systems has increased [2].

Vibration isolation using rubber bearings is one of the most popular methods of passive vibration control. It is known that a seismic isolation rubber bearing, consisting of rubber sheets and steel plates, is effective for an architectural structure whose base is subjected to an earthquake input [3]. In addition, semi-active vibration methods are proposed in the literature. Improvements in electromagnetic force sources and sensors have made this application possible [4,5]. Yoshida and Fujio [6] applied such to base a method in which viscous damping coefficient is changed for vibration control. In recent years, there are studies where active actuators are used for isolation systems in order to isolate the earthquake-induced vibrations. Fukushima et al. [7] developed an active–passive composite tuned mass damper, where it is aimed to reduce wind and earthquake-induced vibrations of tall buildings. Since, there are uncertainties in buildings and system parameters are not constant, different control methods are offered for the active control of structures [8]. Schlacher et al. [9] used a class of control systems for earthquake excited high raised buildings, which consist of a base isolation and an additional active damper and the mechanical model of building is a shear wall structure with nonlinear hysteretic restoring forces. Agarwala et al. [10] designed a fuzzy gain scheduling of PID controller for five-degree-of-freedom structure using two controllers with an actuator and an active-tuned-mass damper. The system is then subjected to earthquake vibrations and wind effects, at different load levels, which are treated as disturbances. Satisfactory vibration suppression is achieved. Al-Dawod et al. [11] applied fuzzy logic controller for active vibration control of tall buildings under wind excitation. Aldemir and Bakioglu [12] applied the analytical solution of the modified linear quadratic regulator problem in active structural control. Yagiz [13] applied sliding mode control for a multi-degree-of-freedom structural system using an active-tuned-mass damper. Ahlawat and Ramaswamy [14] applied fuzzy logic controller (FLC) driven hybrid mass damper for vibration control of seismically excited structures by using multi-objective optimal design method. Guclu [15] designed a fuzzy logic-based controller and PD controller for an actively control device considering a five-degree-of-freedom structure against the ground motion of the destructive earthquake. Guclu [16,17] applied sliding mode and proportional-integral-derivative control for structures with and without an active-mass damper.

Alli and Yakut [18] designed fuzzy sliding-mode control for seismic isolation of earthquake-induced eight-storey structure and the proposed controller was compared with the conventional sliding mode controller. Madan [19] applied active control of earthquake-induced vibrations in building structures using self-organizing and self-learning neural networks.

In this study, a fifteen-degree-of-freedom structural system with active tuned mass damper (ATMD) is modeled and earthquake ground motion is used as input to this building structure. The fuzzy logic and PD controllers are designed to suppress structural vibrations against earthquake using two actuators. This earthquake motion is obtained using the seismic data of Kocaeli Earthquake ($M_w = 7.4$) which resulted in more than 20,000 death in Turkey on 17 August 1999 [20].

2. Dynamic model of fifteen-degrees-of-freedom structural system with ATMD

The structure has fifteen degrees of freedom all in a horizontal direction. Since the destructive effect of earthquakes is a result of horizontal vibrations, in this study the degrees of freedom have been assumed only in this direction. The system is modeled including the dynamics of linear motor which is used as the active isolator. An important element of an active control strategy is the actuators [10]. These are active control devices that expend energy to attenuate disturbances at the corresponding subsystems or reduce the vibration on storeys which they are installed. In this study, two actuators are used to suppress earthquake-induced vibrations. They are installed on the first and fifteenth storeys.

Here two types of actuators are used:

(i) During an earthquake, the maximum inter-storey shear force occurs on the first storey. Assuming equivalent storey stiffness and ultimate capacities, the destructive effect of an earthquake is expected to be the largest on the first storey. Therefore, the active control was applied on the first storey using a linear motor. It supplies control voltage directly to suppress the magnitude of undesirable earthquake vibrations.
(ii) It is well known that the maximum displacements and accelerations are expected from the top storey of structures during an earthquake. Because of that an ATMD with active and passive elements, which are optimally tuned for the first mode of the structural system, is placed over the top storey and a linear motor is used as the active isolator.

The structural system is shown in Fig. 1. Here m_1 is movable mass of the ground storey, these mass of others are m_2, m_3,…, m_{14}, m_{15}, where m_{16} is the mass of the ATMD. x_1, x_2, x_3,…,x_{14}, x_{15} are the horizontal displacements and x_{16} is the displacement of ATMD. x_0 is the earthquake-induced ground motion disturbance to the structure. The masses cover both the ones of storeys and walls over them. All springs and dampers are acting in horizontal direction. The system parameters of a real structure [21] are presented in the Appendix.

The equation of motion of the system is

$$[M]\ddot{x} + [C]\dot{x} + [K]x = Fd + Fu \tag{1}$$

where $x = [x_1\ x_2\ x_3\ x_4\ x_5\ x_6\ x_7\ x_8\ x_9\ x_{10}\ x_{11}\ x_{12}\ x_{13}\ x_{14}\ x_{15}\ x_{16}]^{\mathrm{T}}$, $Fd = [-(c_1\dot{x}_0 + k_1 x_0)\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]^{\mathrm{T}}$ and $Fu = [-Fu\ Fu\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ Fu_{\mathrm{ATMD}}\text{–}Fu_{\mathrm{ATMD}}]^{\mathrm{T}}$. Fd is the force induced by earthquake. Fu and

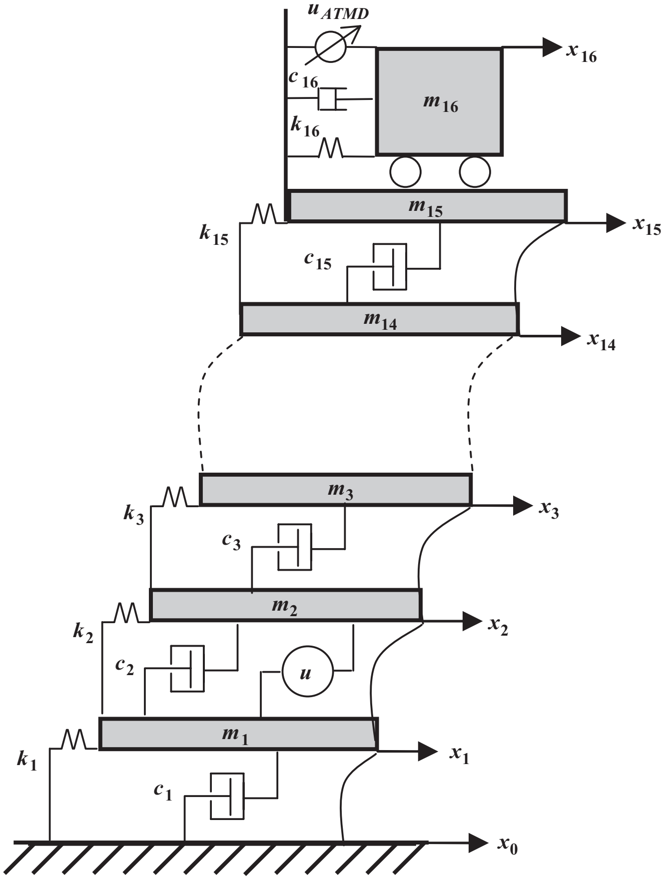


Fig. 1. Physical model of the structural system with ATMD.

Fu_{ATMD} are the control force produced by a linear motor; [*M*], [*C*] and [*K*] are mass, damping and stiffness matrices, respectively, and these are given in the Appendix.

The equations of the linear motors are

$$Ri + K_e(\dot{x}_2 - \dot{x}_1) = u \tag{2}$$

$$Ri_{\mathrm{ATMD}} + K_e(\dot{x}_{16} - \dot{x}_{15}) = u_{\mathrm{ATMD}} \tag{3}$$

u–u_{ATMD} and i–i_{ATMD} are the control voltages and currents of the armature coil, respectively. R and K_e are the resistance value and induced voltage constant of the armature coil. The currents of the armature coil and control forces have the following relation:

$$Fu = K_f i \tag{4}$$

$$Fu_{\mathrm{ATMD}} = K_f i_{\mathrm{ATMD}} \tag{5}$$

where K_f is the thrust constant. The inductance of the armature coil is neglected.

3. The PD controller

The PD control has been used in industry widely as a traditional example. A general control input $u(t)$ is obtained as follows:

$$u(t) = K_P\left[e(t) + \tau_d \frac{\mathrm{d}e(t)}{\mathrm{d}t}\right] \tag{6}$$

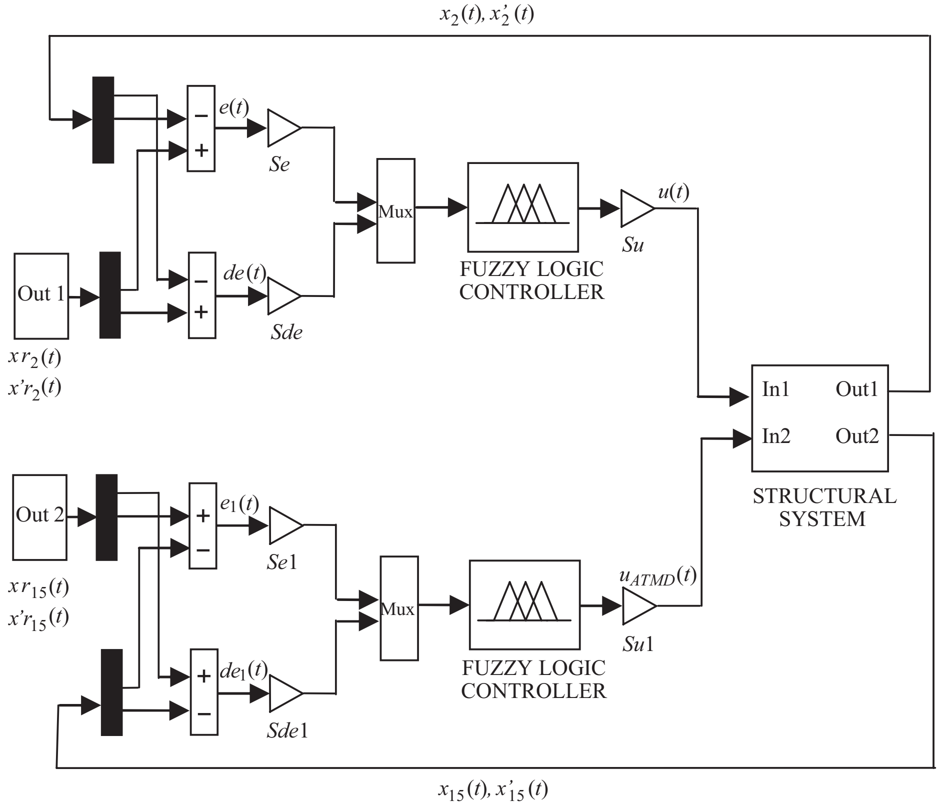


Fig. 2. Closed-loop model of the structure with fuzzy logic controllers.

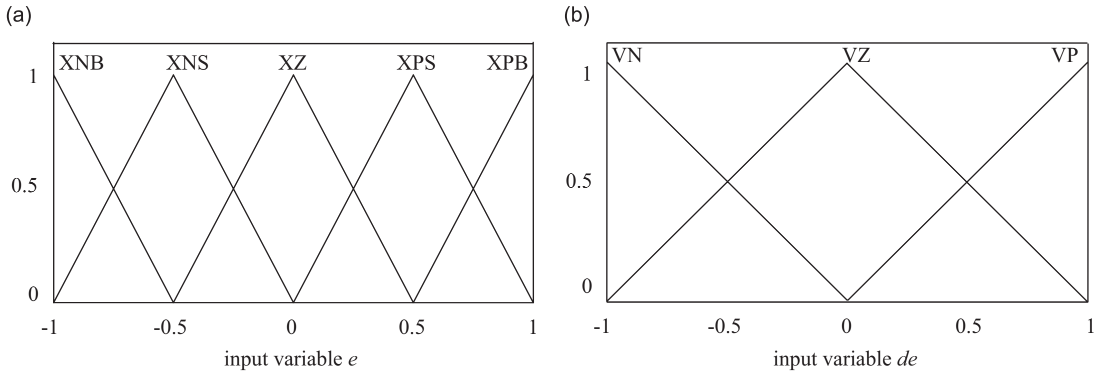
where K_P and τ_d are the proportionality constant and derivative time, respectively [1]. In this study, two actuators, which are installed on the first and fifteenth storeys, are used. Therefore, two PD controllers are used as control algorithm. K_P, τ_d, $K_{P\text{ATMD}}$ and $\tau_{d\text{ATMD}}$ are the values of controller parameters for the first and fifteenth storeys actuators, respectively, which are given in the Appendix.

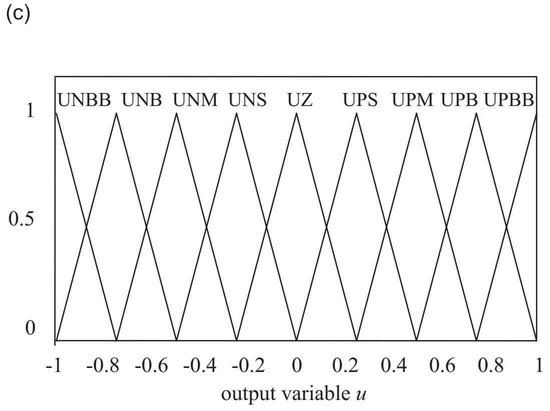
4. The fuzzy logic controller

The aim of this study is to apply the fuzzy logic control to structural systems. Fuzzy logic has come a long way since it was first presented to technical society, when Zadeh [22] published his seminal work "Fuzzy Sets" in the Journal of Information and Control. Since that time, the subject has been the focus of much

Table 1
Rule base for the fuzzy logic controllers

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





(d)

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

Fig. 3. Membership functions of (a) error (e), (b) derivative of error (de/dt), (c) control signal (u) and (d) rules.

independent research. The attention currently being paid to fuzzy logic is most likely the result of present popular consumer products employing fuzzy logic [23]. The superior qualities of this method include its simplicity, satisfactory performance and robust character.

In this study, Matlab Simulink with Fuzzy Toolbox is used. The aim of the fuzzy logic control system for the structural system uses the errors ($e = x_{r2} - x_2, e_1 = x_{r15} - x_{15}$) in the second storey and fifteenth storey motion, and their derivatives ($\mathrm{d}e/\mathrm{d}t = \dot{x}_{r2} - \dot{x}_2, \mathrm{d}e_1/\mathrm{d}t = \dot{x}_{r15} - \dot{x}_{15}$) as the input variable while the control voltages (u) and (u_{ATMD}) are outputs. Reference values ($x_{r2}, \dot{x}_{r2}$) and ($x_{r15}, \dot{x}_{r15}$) are considered to be zero in closed-loop model of the system (Fig. 2).

A model of the two similar rule bases developed by heuristics with error in body bounce motion, pitch motion and velocity as input variables are given in Table 1, where *P*, *N*, *Z*, *B*, *M*, *S* represent positive, negative, zero, big, medium and small, respectively. A trial and error approach with triangular membership functions has been used to achieve a good controller performance. The membership functions for both scaled inputs (*e*, *de*) and output (*u*) of the controller have been defined on the common interval [−1, 1] (Fig. 3). Scaling factors (*Se*, *Sde*, *Su* and *Se*1, *Sde*1, *Su*1) are used to set *e*, *de* and *u* in Fig. 2 [24]. The values of scaling factors are presented in the Appendix.

The first rule in Table 1 is given as

IF *e* is XNB and d*e*/d*t* is VN THEN *u* is UNB.

All the rules are written using Mamdani method to apply to fuzzification in Fig. 3d. In this study, the centroid method is used in defuzzification.

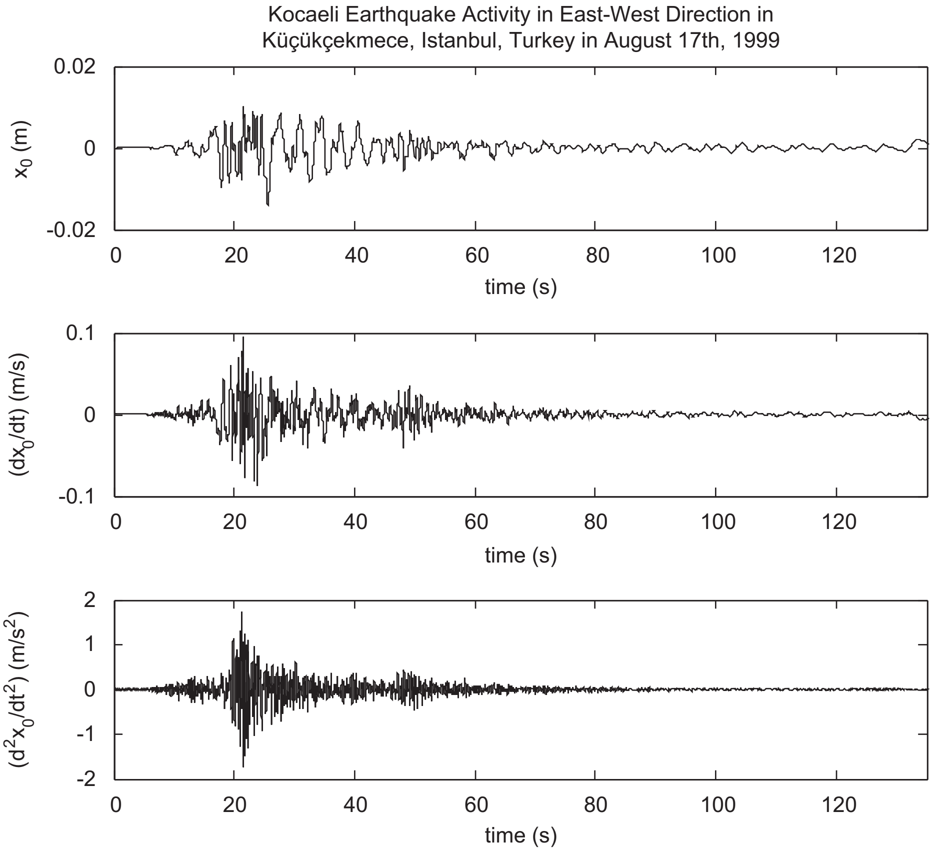


Fig. 4. Kocaeli Earthquake excitation input to the structure.

5. Earthquake excitation and the response of the structural system

A structural system has been simulated against the earthquake ground motion of Kocaeli earthquake ($M_w = 7.4$) in Turkey in 17 August 1999. Earthquake ground motion is used as input to a building structure.

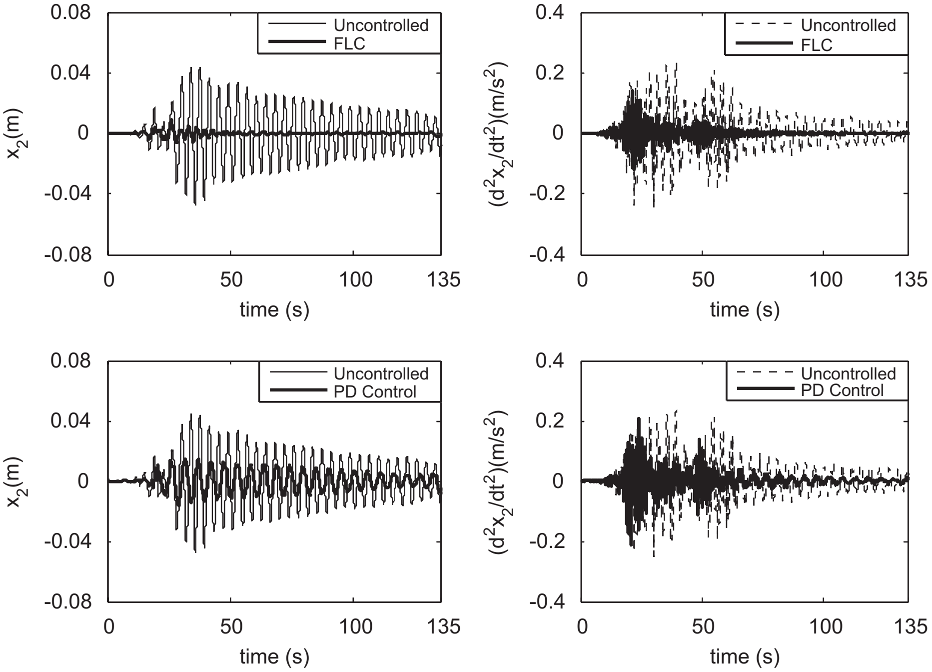


Fig. 5. Controlled and uncontrolled displacement and acceleration time responses of second storey.

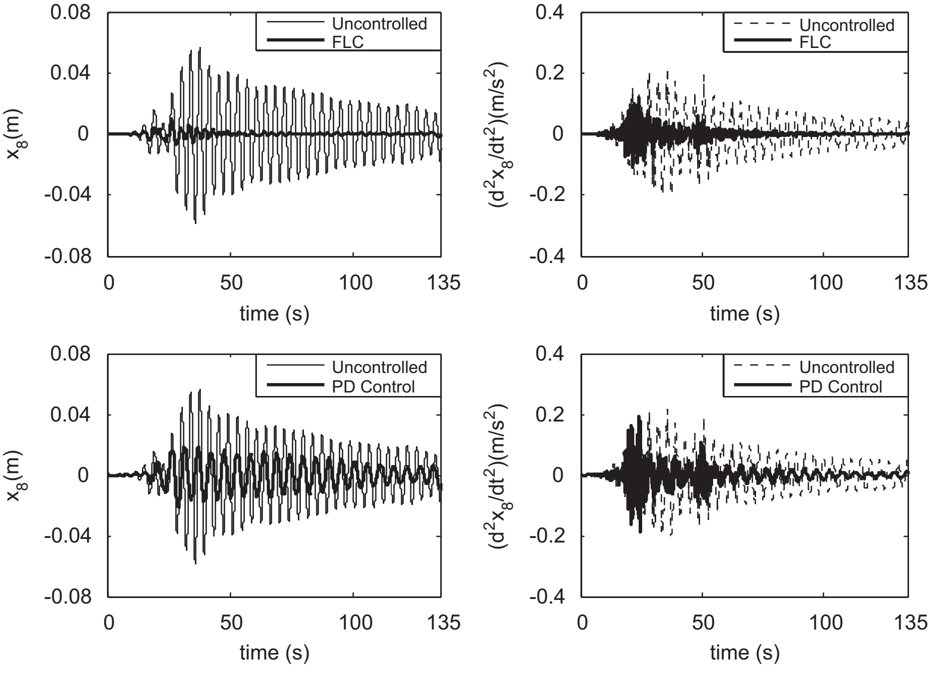


Fig. 6. Controlled and uncontrolled displacement and acceleration time responses of eighth storey.

Accelerations are recorded at the Kandilli Observatory and Earthquake Research Institute strong motion station at the Kucukcekmece Nuclear Research Center in Istanbul, Turkey during 17 August 1999 main shock in Fig. 4 [20].

The displacements of the related storeys are planned to estimate through displacements on them after online integration. This integration includes the necessary high–low pass filters to get rid of the effects of noise and other unmodeled dynamics. When the horizontal displacements and accelerations responses of the structure are considered, essential performance requirements are the safety of the structures and comfort level of the occupants.

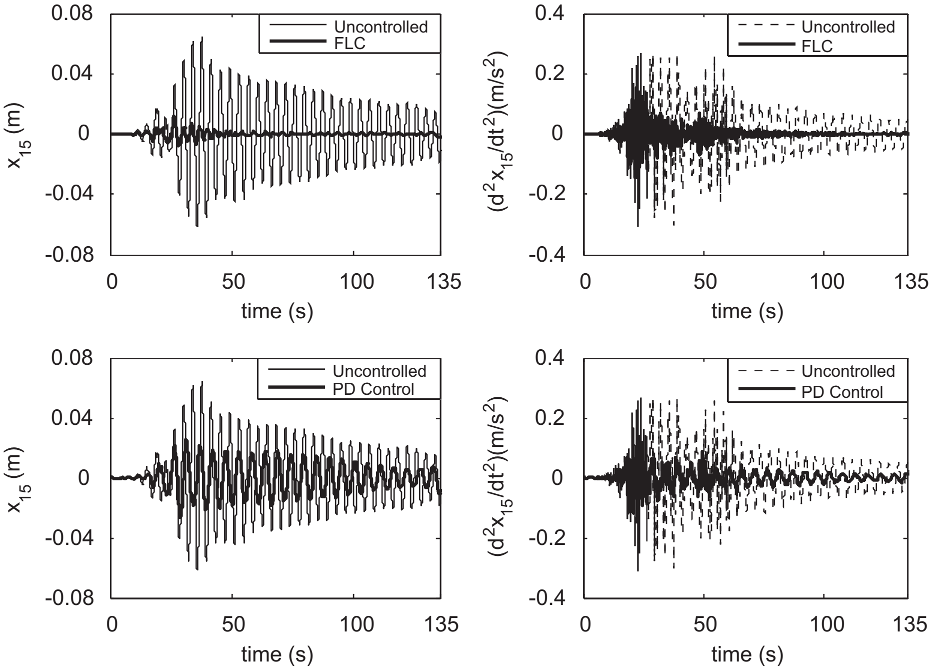


Fig. 7. Controlled and uncontrolled displacement and acceleration time responses of fifteenth storey.

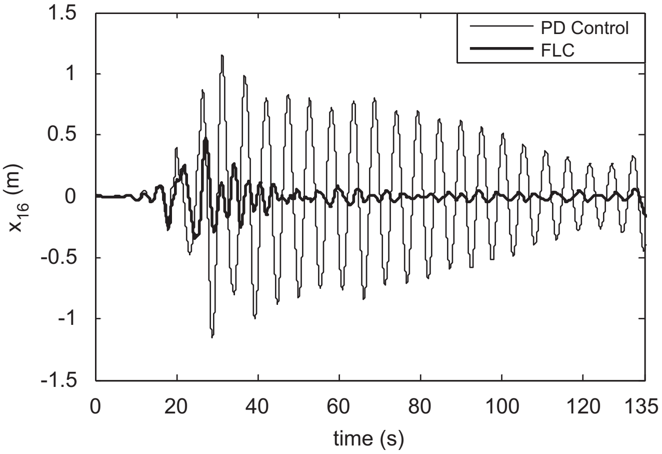


Fig. 8. Time history of ATMD displacements.

Figs. 5, 6 and 7 show the time responses of the second, eighth and fifteenth storey displacements and accelerations, respectively, for both controlled and uncontrolled cases. As shown in Figs. 5–7, vibration amplitudes of storeys are decreased successfully with fuzzy logic controller.

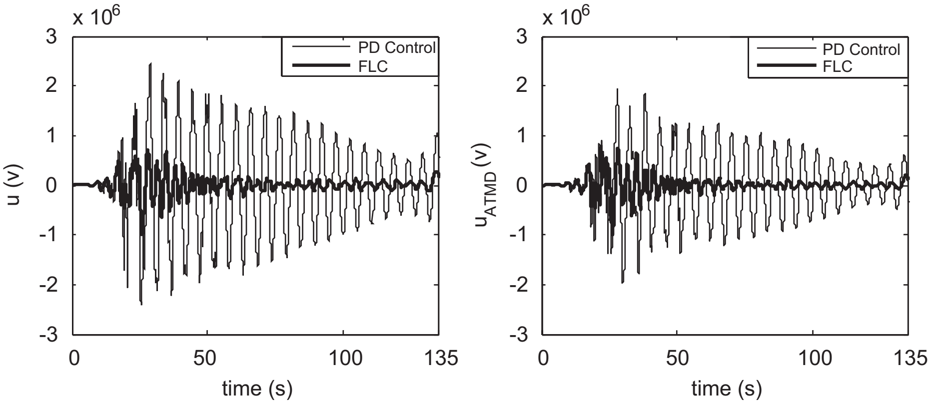


Fig. 9. Time history of control voltages.

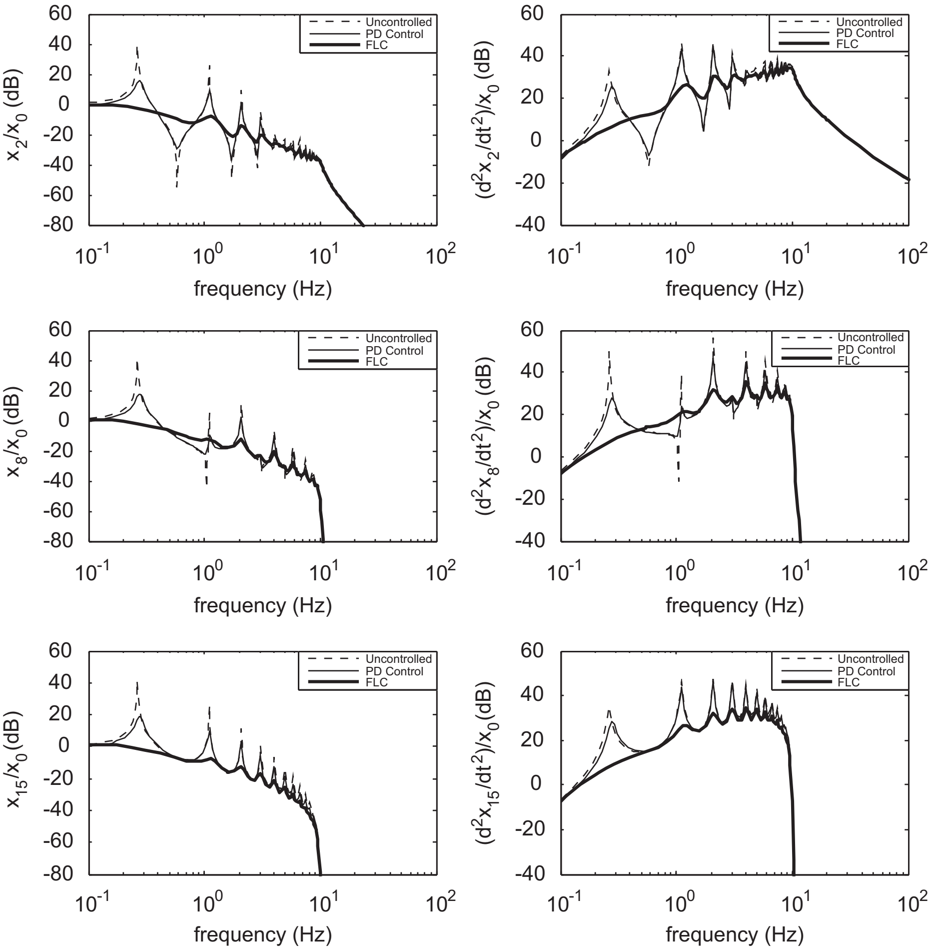


Fig. 10. Controlled and uncontrolled frequency responses of the second, eighth and fifteenth storeys.

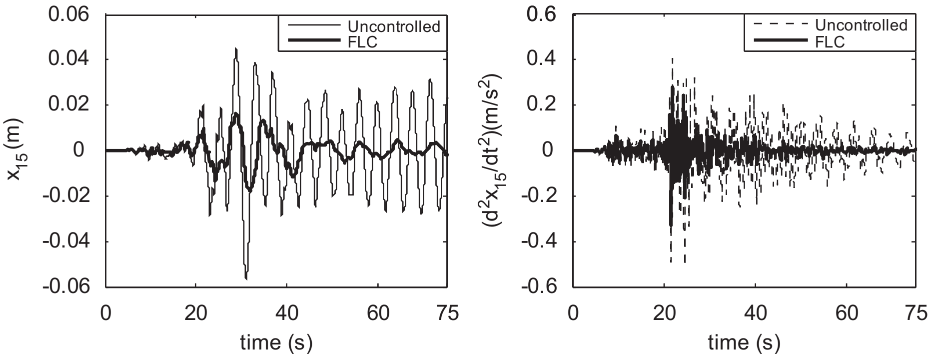


Fig. 11. Controlled and uncontrolled time responses of fifteenth storey against Kobe Earthquake.

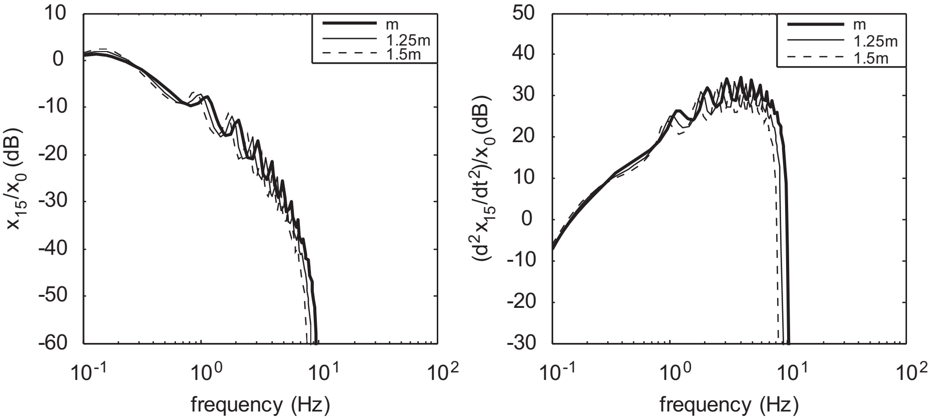


Fig. 12. Frequency responses of the fifteenth storey for changing mass parameters.

Fig. 8 shows the time history of ATMD displacements. Fig. 9 demonstrates the change in control voltage inputs for the two controllers.

Fig. 10 shows the frequency responses of the second, the eighth and the fifteenth storey displacements and accelerations, for both controlled and uncontrolled cases. Since the system has fifteen degrees of freedom, there are fifteen resonance values at 0.26, 1.10, 2.07, 3.05, 4.01, 4.94, 5.81, 6.63, 7.37, 8.04, 8.62, 9.10, 9.48, 9.76 and 9.93 Hz. The natural frequency of ATMD is tuned for the first mode.

As expected the lower curves belong to the controlled systems. When the response plots of the structural systems with uncontrolled, fuzzy logic and PD controlled cases are compared, a superior improvement in terms of magnitudes with fuzzy logic one has been witnessed (Fig. 10). Therefore, at the resonance values of the response of the storeys with FLC, satisfactory results are reached.

Performance of designed FLC is checked against different disturbances using ground motion of the Kobe Earthquake (Fig. 11). This earthquake motion is obtained using the seismic data of Kobe earthquake in Japan in 1995 [25]. Performance of the FLC must not get worse for different disturbances. Simulation results are shown in Fig. 11 for the time responses of fifteenth storey which has maximum displacements and accelerations during an earthquake.

The robustness of the controller has been demonstrated through the uncertainty in mass (25% and 50% variation from initial mass) of the structure. Robustness of designed FLC has been checked using displacement and acceleration frequency responses of fifteenth storey against the uncertainties in mass parameters of each storey in Fig. 12. Performance of the FLC must not get worse against changing system parameters. Therefore, mass values have been increased to 25% and 50%.

It has been observed in Figs. 11 and 12 that the performance of the fuzzy logic controller for different loads and earthquake ground motion has shown a satisfactory robust character.

6. Conclusion

In this study, fuzzy logic and PD controllers have been designed for a multi-degree-of-freedom structural system having the parameters of a real building and simulation results have been presented. The main idea behind proposing fuzzy logic controller has great potential in active structural control. Since the destructive effect of earthquakes is a result of horizontal vibrations, the degrees of freedom were assumed only in this direction. The system is modeled including the two actuators which are installed on first and fifteenth storey. The structural system is then subjected to Kocaeli Earthquake vibrations effects, which are treated as disturbance. The simulation results exhibit that the implementation of fuzzy logic controller shows a good response as far as absorbing the vibration due to earthquake effects. Essential performance requirements for the safety of the structures and comfort level for the occupants are achieved. It is well known that for frequency responses, the first mode is the most dangerous for structures and the maximum displacements are expected the top storey of structures during an earthquake. Therefore, the first mode is compressed and displacements and accelerations of fifteenth storey are minimized succesfully using the fuzzy logic controller. Also, performance of the designed FLC is checked for different disturbances using ground motions of Kocaeli and Kobe Earthquakes. Simulations results show that the proposed controllers have a satisfactory performance. The designed fuzzy logic controller brought better active control performance than PD controller. The improvement in resonance values and the decrease in vibration amplitudes support this result.

Appendix

Mass matrix:

$$[M] = \begin{bmatrix} m_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & m_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & m_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & m_5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & m_6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & m_7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_{10} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_{12} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_{13} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_{14} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_{15} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_{16} \end{bmatrix}$$

Damping matrix:

$$[C] = \begin{bmatrix}
c_1+c_2 & -c_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-c_2 & c_2+c_3 & -c_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -c_3 & c_3+c_4 & -c_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -c_4 & c_4+c_5 & -c_5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -c_5 & c_5+c_6 & -c_6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -c_6 & c_6+c_7 & -c_7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -c_7 & c_7+c_8 & -c_8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -c_8 & c_8+c_9 & -c_9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -c_9 & c_9+c_{10} & -c_{10} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -c_{10} & c_{10}+c_{11} & -c_{11} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -c_{11} & c_{11}+c_{12} & -c_{12} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -c_{12} & c_{12}+c_{13} & -c_{13} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -c_{13} & c_{13}+c_{14} & -c_{14} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -c_{14} & c_{14}+c_{15} & -c_{15} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -c_{15} & c_{15}+c_{16} & -c_{16} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -c_{16} & c_{16}
\end{bmatrix}$$

Stiffness matrix:

$$[K] = \begin{bmatrix}
k_1+k_2 & -k_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-k_2 & k_2+k_3 & -k_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -k_3 & k_3+k_4 & -k_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -k_4 & k_4+k_5 & -k_5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -k_5 & k_5+k_6 & -k_6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -k_6 & k_6+k_7 & -k_7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -k_7 & k_7+k_8 & -k_8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -k_8 & k_8+k_9 & -k_9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_9 & k_9+k_{10} & -k_{10} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_{10} & k_{10}+k_{11} & -k_{11} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_{11} & k_{11}+k_{12} & -k_{12} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_{12} & k_{12}+k_{13} & -k_{13} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_{13} & k_{13}+k_{14} & -k_{14} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_{14} & k_{14}+k_{15} & -k_{15} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_{15} & k_{15}+k_{16} & -k_{16} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_{16} & k_{16}
\end{bmatrix}$$

Parameters of the fifteen degrees of freedom of a realistic structural system (see Table A1).

Table A1

Mass parameters (kg)	Stiffness parameters (N/m)	Damping parameters (N s/m)
$m_1 = 450{,}000$	$k_1 = 18050{,}000$	$c_1 = 26{,}170$
$m_2 = 345{,}600$	$k_2 = 340{,}400{,}000$	$c_2 = 293{,}700$
$m_3 = 345{,}600$	$k_3 = 340{,}400{,}000$	$c_3 = 293{,}700$
$m_4 = 345{,}600$	$k_4 = 340{,}400{,}000$	$c_4 = 293{,}700$
$m_5 = 345{,}600$	$k_5 = 340{,}400{,}000$	$c_5 = 293{,}700$
$m_6 = 345{,}600$	$k_6 = 340{,}400{,}000$	$c_6 = 293{,}700$
$m_7 = 345{,}600$	$k_7 = 340{,}400{,}000$	$c_7 = 293{,}700$
$m_8 = 345{,}600$	$k_8 = 340{,}400{,}000$	$c_8 = 293{,}700$
$m_9 = 345{,}600$	$k_9 = 340{,}400{,}000$	$c_9 = 293{,}700$
$m_{10} = 345{,}600$	$k_{10} = 340{,}400{,}000$	$c_{10} = 293{,}700$
$m_{11} = 345{,}600$	$k_{11} = 340{,}400{,}000$	$c_{11} = 293{,}700$
$m_{12} = 345{,}600$	$k_{12} = 340{,}400{,}000$	$c_{12} = 293{,}700$
$m_{13} = 345{,}600$	$k_{13} = 340{,}400{,}000$	$c_{13} = 293{,}700$
$m_{14} = 345{,}600$	$k_{14} = 340{,}400{,}000$	$c_{14} = 293{,}700$
$m_{15} = 345{,}600$	$k_{15} = 340{,}400{,}000$	$c_{15} = 293{,}700$
$m_{16} = 104{,}918$	$k_{16} = 280{,}000$	$c_{16} = 597{,}000$

FLC input–output scaling factors for actuator which is installed first storey	FLC input–output scaling factors for ATMD	Linear motor parameters
$Se = 40$	$Se1 = 5$	$R = 4.2\,\Omega$
$Sde = 0.9$	$Sde1 = 0.9$	$K_f = 2\,\mathrm{N/A}$
$Su = 5{,}800{,}000$	$Su1 = 24{,}700{,}000$	$K_e = 2\,\mathrm{V}$

PD controller parameters for actuator which is installed first storey	PD controller parameters for ATMD
$K_P = 140{,}000{,}000$	$K_{P\mathrm{ATMD}} = 8{,}750{,}000$
$\tau_d = 0.285$	$\tau_{d\mathrm{ATMD}} = 6.285$

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