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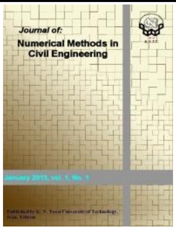

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Effects of the structural period variations and near field earthquakes on a fuzzy controller performance for the variably baffled tuned liquid damper

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Abstract:

Structural control as a countermeasure against unwanted structural vibrations is divided into three general categories known as passive, active, and semi-active. Among various structural control devices, the tuned Liquid Damper (TLD) can lend itself well to reducing structural demands through all of the control scenarios. In this paper, demands of Single degree of freedom (SDOF) structures subjected to near and far field ground motions are controlled by a recently developed TLD, named a variably baffled tuned liquid damper (VBTLD), through semi-active and passive control. The effects of the controlled structural period variations on the performance of the linear optimal control algorithm and a fuzzy controller have been examined comparatively. Results show that the semi-active fuzzy controller has better performance than the linear optimal control algorithm. The fuzzy controller can reduce both RMS and peak responses, effectively and its performance improves with increasing the controlled structural period. Furthermore, the fuzzy controller has the same controlling effects under near and far-field earthquakes.

1. Introduction

The tuned liquid damper (TLD) was initially used as a passive device to reduce wind-induced vibrations in tall buildings[1-3]. The fluid turbulence in the rigid reservoir of this damper causes it to excite even with the smallest movements of the primary structure. This mechanism has been studied as a method for energy depletion[4, 5]. Damati[6] illustrated that using TLDs can reduce seismic responses of an 8-story steel building by up to 60% even in strong earthquakes. However, the control forces of conventional passive TLDs against strong excitations are inadequate. To achieve greater control forces, a large tank containing a large volume of liquid is required, which practically leads to an undesirable great mass ratio.

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To improve damping without increasing the liquid volume, Tait et al.,[7] inserted some slat screens inside the liquid tank and considered the TLD linear and nonlinear models numerically and experimentally. The linear model can provide an estimate of the TLD's superior performance while compared to experimental results, the nonlinear model is more accurate. Love and Tait [8] have also studied experimentally the effects of different states of these plates. Zahrai et al. [9] proposed a rectangular tank liquid damper with adjustable baffles named a variably baffled tuned liquid damper (VBTLD). They installed two rows of oppositely rotating vertical baffles inside the damper and used it for passive control of an MDOF structure. Results showed that the baffles can significantly enhance energy dissipation.
Despite improving damping capacity, the TLD’s major drawback is yet to be passive, consequently, it is effective in a narrow frequency band and is sometimes not applicable to MDOF structures. Enayati and Zahrai [10] in their numerical and experimental studies used the VBTLD for passive control of a 5 degrees of freedom structure. Under each of

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the excitations, they examined the damper performance per different angles of the baffles' orientation. They determined the VBTLD's damping coefficient for various baffles' angle from laboratory tests. They observed that per each excitation, there is an angle for which the damper can impose the highest controlling effects. Therefore, they concluded that if a suitable semi-active algorithm is applied to rotate the baffles instantly, the VBTLD would have a higher capacity to dissipate input energy. To confirm the VBTLD performance improvement through semi-active control, Enayati and Zahrai [11] in another numerical study used a linear quadratic regulator algorithm (LQR) to control seismic responses of SDOF structures under near and far field ground motions. In this semi-active scenario, using input and output feedback, the VBTLD can adjust the baffle angle in real-time leading to changes in the exerted damping. Their investigations showed that the performance of the semi-active VBTLD is promising and results under near-field earthquakes are better than those of far-field records.

Regarding the severe nonlinear nature of the TLD, design details and the control algorithm are very effective in achieving optimal performance in a semi-active control scenario. Various semi-active control strategies have been proposed in previous studies from which the most common are LQR, LQG, and slip mode controller [12-14]. A semi-active control device depending on its properties can do better using a particular control algorithm whereas that algorithm would not be suitable for other devices[15]. In recent years, fuzzy logic-based control algorithms have been utilized by many scholars in the structural control area. In fact, due to complexities in the behavior of nonlinear systems, fuzzy-based algorithms can be used more effectively than other methods for control purposes with much less dependency on complex mathematical equations[16]. Teng et al. [17] used a max-min inference engine and a mass center defuzzifier to design a fuzzy controller. They studied the overlap ratio of membership functions and found the ratio of 0.3 has the best performance. Samali et al. [18] investigated wind effects on a 76-storey structure. In this study, the effects of time step changes and modeling errors on the results and stability of several controllers including a fuzzy controller were evaluated. Results showed that the fuzzy controller, in addition to flexibility against modeling errors, is also less sensitive to the time step. Kim and Horelbas[19] proposed a multi-input and output model for a fuzzy nonlinear controller. They studied an eight-story building structure employing magneto-rheological (MR) dampers and showed that the proposed controller has better performance in comparison to passive control. Pourzinli et al. [20] used a fuzzy controller with a mamdani max-min inference motor and a mass center defuzzifier combined with genetic algorithms to design and optimize parameters of active tuned mass dampers embedded on an 11-story shear frame. Results showed that the designed fuzzy controller is better than other controllers such as linear quadratic regulator control methods. Zahrai and Shafizadeh [21] studied a 76-storey benchmark RC building (in Melbourne) under a wind excitation. They considered the effects of modeling errors on the controller performance and observed that using fuzzy control has better results compared to passive control and leads to a higher response reduction.

In [11], the semi-active VBTLD was designed using the LQR method which, of course, had promising results in terms of its controlling effects. LQR is an explicit and stable controller that is very easy to use [22] however, as the constraints of the optimization problem increase, its performance decreases and for systems with a severe nonlinear nature (such as TLDs), its performance is along with some challenges. Furthermore, it is difficult to minimize the responses that occur in the initial moments of excitations such as near-fault ground motions[5]. Therefore, in this paper, the semi-active VBTLD performance by using a fuzzy controller is investigated for SDOF structures subjected to near and far-field earthquakes. According to previous studies, fuzzy controllers perform better in the case of nonlinear systems, therefore, it is expected that they would be more capable of revealing the controlling capacity of VBTLD. Moreover, to better scrutinize the controller robustness, the effects of the controlled structural period variations on the controller performance have been investigated.

2. Variably Baffled Tuned Liquid Damper (VBTLD)

In a TLD the dissipation mechanism consists of the boundary layer friction, the fluid turbulence, and the wave refraction. For a VBTLD, the baffles' rotation changes the damper frequency and the flow lines' curvature and consequently creates another energy dissipation mechanism. Therefore, the VBTLD has a higher energy dissipation capacity compared to a conventional TLD while the consumed energy to control the baffles' rotation is trivial (in the order of a battery).

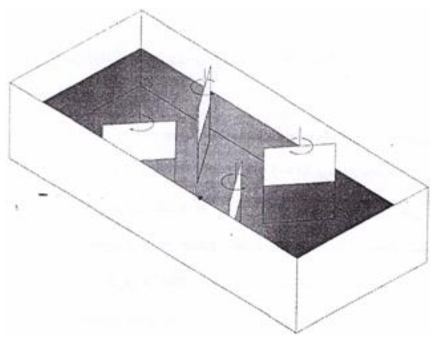


Fig. 1: schematic of VBTLD

The VBTLD simulated here, has four baffles in two vertical rows rotating similarly (Figure 1). The similar rotation of the baffles increases the wave fracture and the curvature of the flow path which amplifies energy dissipation in the damper.

3. The fuzzy Controller

Fuzzy systems are based on knowledge or rules. The core of a fuzzy system is a database consisting of fuzzy if-then rules. A fuzzy rule is an expression in which some words are denoted by continuous belonging functions. Fuzzy systems are precisely defined systems and fuzzy control is a special type of nonlinear control. Although fuzzy systems describe uncertain phenomena, the fuzzy theory by itself is exact[23]. In other words, fuzzy systems are multi-input and single-output mappings, with obtainable mathematical formulas, from a real vector to a real scalar. An important aspect of the fuzzy systems theory is providing a systematic process to transform a knowledge database into a nonlinear mapping. This is why we will be able to use knowledge-based systems in engineering applications. In general, fuzzy systems can be summarized in the following three types[24]:

1- Pure fuzzy systems
2- Takagi-Sugeno-Kang (TSK) fuzzy systems
3- Fuzzifier and defuzzifier systems

The fuzzy controller used in this study to rotate the baffles during dynamic excitations and impose semi-active control is a fuzzifier and defuzzifier system. In this controller, displacement and velocity values are the inputs, and the damping coefficient (the baffle angle) is the output.

A fuzzifier converts valued variables into a fuzzy set using membership functions[24]. For each input, 8 triangular membership functions are used, as shown in Figure 2. P indicates a positive and N indicates a negative input in these functions. S, M, L, and VL also represent small, medium, large, and very large inputs, respectively. PVL, for example, represents a very large positive velocity or displacement input. These functions are used for both velocity and displacement values. According to Teng et al.[17], the overlap coefficient for membership functions should be between 0.2 and 0.7, so in this study, this coefficient opted for 0.5.

To generate the damping coefficient as the output, a defuzzifier converts the fuzzy set into a valued variable using 6 triangular membership functions with an overlap factor of 0.5 (Figure 3). Totally, according to membership relationships, 64 rules were defined for the controller. These rules are given in Table 1. The Bang-Bang model is used to define these rules.

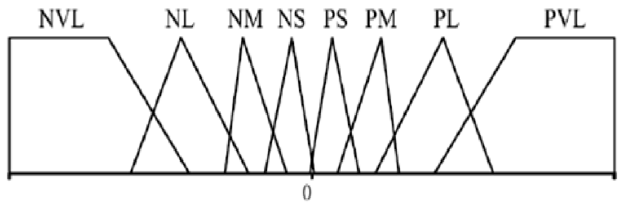


Fig. 2: A schematic of defined membership functions

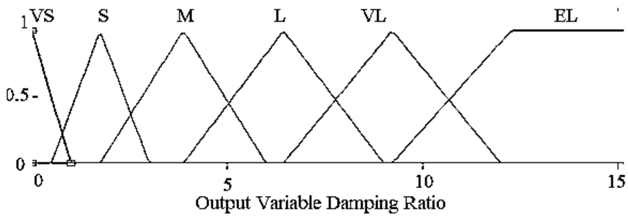


Fig. 3: Defined membership functions for outputs

4. The structural model

To evaluate the performance of a fuzzy controller in semi-active control using the VBTLD, semi-active control with the linear optimal control algorithm and passive control using the VBTLD with fixed baffles are also incorporated in the analysis, resulting in a total of 720 analyses. In the passive control, the baffles' angle is 72 degrees, which represents the VBTLD with its maximum damping capability.

Table 2 summarizes specifications of the models used to investigate the effect of changing the controlled structural period on the performance of the VBTLD. For the SDOF models the damping coefficient is equal to 5 percent of the critical damping. In the semi-active control scenarios, a fuzzy controller and the linear optimal control algorithm are used to control the baffles' rotation. To determine the optimal baffle's angle at each time instant during input excitations, the damping coefficient of the VBTLD should be known per each baffle's angle obtained from shaking table tests carried out by Enayati and Zahrai[10] (Figure 4) (Table 3). They determined the damping coefficient values per different angles and excitation frequencies using the equivalent viscous damping method [25]. The baffles' rotation in the VBTLD, used here, is consistent with the results of the experimental studies by Enayati and Zahraei [10]. In table 3, the angle of 90 indicates that the baffles are closed and the tank is divided into three equal parts, and the zero value indicates that the baffles are fully open.

Table 1: Fuzzy rules

Structural Displacement	Structural Velocity							
	NVL	NL	NM	NS	PS	PM	PL	PVL
NVL	EL	EL	EL	VL	S	S	VL	EL
NL	EL	EL	EL	L	M	S	L	VL
NM	VL	L	M	S	S	S	S	L

NS	L	M	S	VS	VS	S	M	L
PS	L	M	S	VS	VS	S	M	L
PM	L	S	S	S	S	M	L	VL
PL	VL	L	S	M	L	EL	EL	EL
PVL	EL	VL	S	S	VL	EL	EL	EL

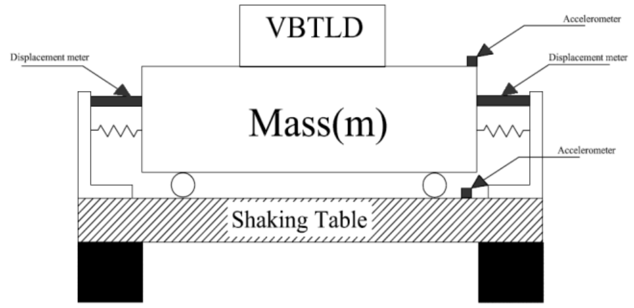


Fig. 4: Damped structural model in shaking table test [10]

Experimental results of the study [10] have been used to verify the numerical modeling and the fuzzy controller performance. For this purpose, the controller is subjected to a harmonic excitation with a frequency of 1.25 Hz and an intensity of 0.1 g. According to the Experimental results for this case, the best baffle angle is 72 degrees, so the controller must reach this value at least time. As can be seen in Figure 5, the displacement response of the SDOF model with the fuzzy controller is in good agreement with the experimental results which confirms the outputs of the code implemented in the MATLAB [26] environment to analyze the SDOF model.

Input excitations, 5 near-field and 7 far-field earthquake records with the moment magnitude (M_w) between 6.5 to 7.5 are selected from recorded strong ground motions of the Next Generation Attenuation (NGA) library (http://peer.berkeley.edu/nga). The earthquake records, selected for this study, with their characteristics are summarized in Table 4.

Table 2: The structural models

	Mass (Kg)	Stiffness (N/m)	Structural Period (Sec)	Damping Coefficient (N. Sec/m)
1	100	14000	0.53	118.3
2	200	14000	0.75	167.3
3	300	14000	0.92	204.9
4	400	14000	1.06	236.6
5	500	14000	1.19	264.6
6	600	14000	1.3	289.8
7	700	14000	1.4	313.0
8	800	14000	1.5	334.7
9	900	14000	1.59	355.0
10	1000	14000	1.68	374.2
11	1100	14000	1.76	392.4
12	1200	14000	1.84	409.9
13	1300	14000	1.91	426.6
14	1400	14000	1.99	442.7
15	1500	14000	2.06	458.3

Table 3: The damping ratio versus baffle angles and excitation frequencies [10]

	Excitation frequency						
Baffle Angle	0.5	1.25	1.5	2	3	5	10
0	0.092	0.092	0.093	0.095	0.096	0.098	0.102
9	0.095	0.093	0.095	0.098	0.100	0.101	0.108
18	0.097	0.094	0.097	0.100	0.103	0.107	0.115
27	0.098	0.097	0.099	0.107	0.109	0.111	0.121
36	0.101	0.105	0.106	0.113	0.114	0.121	0.127
45	0.105	0.106	0.108	0.109	0.115	0.126	0.136
54	0.106	0.108	0.110	0.112	0.117	0.129	0.141
63	0.112	0.110	0.113	0.116	0.122	0.136	0.145
72	0.114	0.115	0.118	0.123	0.130	0.138	0.153
81	0.110	0.114	0.120	0.121	0.127	0.136	0.150
90	0.107	0.111	0.116	0.120	0.126	0.133	0.146

5. Results

In this study, seismic records from the 5 near-field and 7 far-field events are used to evaluate the performance of a fuzzy controller in semi-active control using the VBTLD. Figure 6 compares the performance of passive control and semi-active fuzzy control on seismic responses. The importance of this comparison is that in the passive control state, the VBTLD with a baffles' angle of 72 degrees is considered, which is the case where this damper exerts the maximum damping. Therefore, comparing semi-active fuzzy control with the maximum damping state can effectively determine its performance level, as during semi-active control, the maximum damping is not always applied to the structure. In the Figure, the displacement time history from the fuzzy and passive control for the SDOF structure with a period value of 0.92 seconds is shown under the Kobe earthquake. According to this figure, the performance comparison between the fuzzy and passive control is important because, in the passive control, the VBTLD has a baffle angle of 72 degrees, which represents the configuration that generates the maximum damping value. Therefore, a comparison between the fuzzy semi-active control and the maximum damping configuration of the VBTLD can effectively evaluate its performance. As observed, the fuzzy control suppresses the maximum structural response and simultaneously results in the response reduction during all

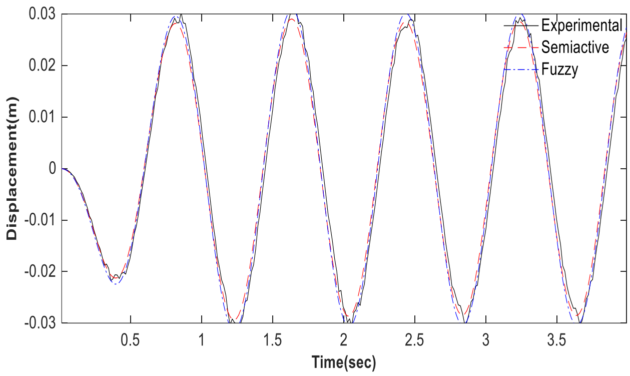


Fig. 5: The structural displacement response to verify the designed controller

Table 4: Ensemble of ground motions

	YEAR	*EVENT*	*STATION*	*PGA (G)*
Near field Records				
1	1989	Loma Prieta	LGPC	0.42
2	1995	Kobe	KJMA	0.82
3	1994	Northridge	Olive view	0.6
4	1992	Cape Mendocino	Petrolia	0.59
5	1994	Northridge	Rinaldi	0.84
Far field Records				
1	1952	Kern County	Taft	0.16
2	1989	Loma Prieta	Cliff-House	0.07
3	1979	Imperial Valley	Calexico	0.17
4	1999	Kocaeli	Ambarli	0.25
5	1992	Big Bear	Desert Hot Spr.	0.23
6	1994	Notrhridge	Century CCC	0.26
7	1989	Loma Prieta	Presideo	0.1

the excitation moments. This implies the better performance of the fuzzy control.

In Figure 7, it can be observed that under the Cliff-House earthquake record, compared to the passive control, using the fuzzy control to rotate the baffles leads to a higher reduction in the structural acceleration response. In this figure, for better clarity, a portion of the structural response time history between 10 to 20 seconds is shown. Therefore, Figures 6 and 7 display that the fuzzy scheme used in the semi-active control by the VBTLD is more effective than the passive control to diminish the displacement and acceleration responses.

The performance comparison of the semi-active and passive controls to decrease the root mean square (RMS) of the structural displacement is demonstrated in Figure 8. This figure indicates how much the fuzzy semi-active control has reduced the structural displacement more than the passive control, in percentage. According to this figure, the fuzzy control consistently imposes a higher decrease compared to the passive control for both far-field and near-field seismic excitations. Furthermore, the reduction in the RMS of the acceleration and base shear responses by the fuzzy semi-active control compared to the passive control can be observed in Figures 9 and 10. In all cases, the fuzzy control exhibits a better performance compared to the passive control, implying its effectiveness. It is to be noted that in the passive control, the baffle angle is set to 72 degrees, active control compared to the passive control can be observed in Figures 9 and 10. In all cases, the active control compared to the passive control can be observed in Figures 9 and 10. In all cases, the fuzzy control exhibits a better performance compared to the passive control, implying its effectiveness. It is to be noted that in the passive control, the baffle angle is set to 72 degrees, which corresponds to the maximum damping for the VBTLD. On the other hand, the comparison of the fuzzy control performance under far-field and near-field earthquakes reveals that the fuzzy control performs better under near-field earthquakes. Furthermore, for the structural periods between 0.92 to 1.5 seconds, the response reduction under near-field excitation is higher than in other periods. The most reduction is observed for the structural period of 0.92 seconds, as the differences in the RMS reduction of the displacement, acceleration, and base shear responses are 43%, 39%, and 40%, respectively.

Another noteworthy observation from the results is that the reduction in the RMS responses is higher than the maximum responses. This finding suggests the higher effectiveness of the fuzzy controller, as it is capable of decreasing RMS responses as well as maximum structural demands.

Another noteworthy observation from the results is that the reduction in the RMS responses is higher than the maximum responses. This finding suggests the higher effectiveness of the fuzzy controller, as it is capable of decreasing RMS responses as well as maximum structural demands. Moreover, according to previous studies, semi-active control methods generally cannot simultaneously reduce the displacement and acceleration responses more than passive control while the designed fuzzy controller has successfully reduced both the displacement and acceleration responses.

To investigate the effects of the controlled structural period variations on the performance of the fuzzy algorithm, the fuzzy semi-active control results can be compared with the results of the semi-active optimal linear control algorithm. Figure 11 represents the maximum reduction values (in percentage) of the displacement response under the fuzzy semi-active control compared to the optimal linear semi-active control. It can be observed that the maximum reduction values achieved by the fuzzy control under the

Kobe and Northridge earthquake records are approximately 14% and 11%, respectively. Furthermore, as evident from this figure, it is clear that the fuzzy control performance compared to the optimal linear control will be enhanced with an increase in the structural period.

This trend can also be observed for the RMS responses, as shown in Figures 12 to 14. In these figures, differences between the fuzzy semi-active control and the optimal linear semi-active control in the RMS response reduction (in percentage) are displayed for displacement, acceleration, and base shear under near and far-field earthquakes. As observed in Figure 12, the displacement reduction is the

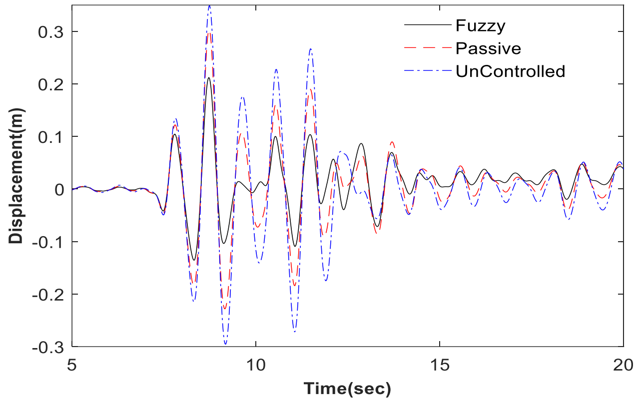


Fig. 6: The displacement response of the structure with a period of 0.92 seconds under the Kobe near field earthquake

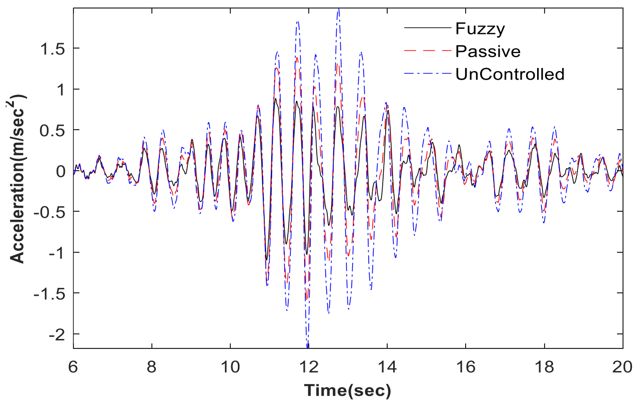
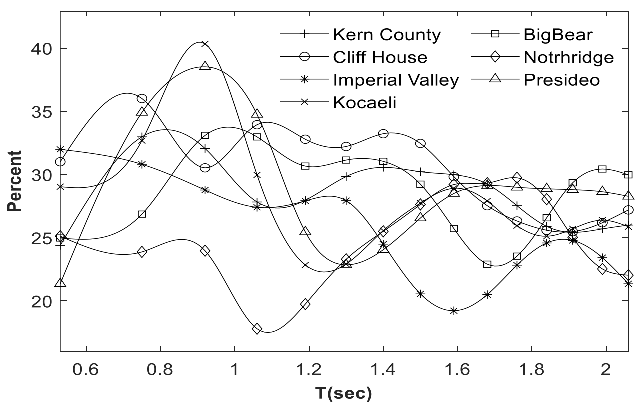


Fig. 7: The acceleration response of the with a period of 0.53 seconds under the Cliff House far-field earthquake



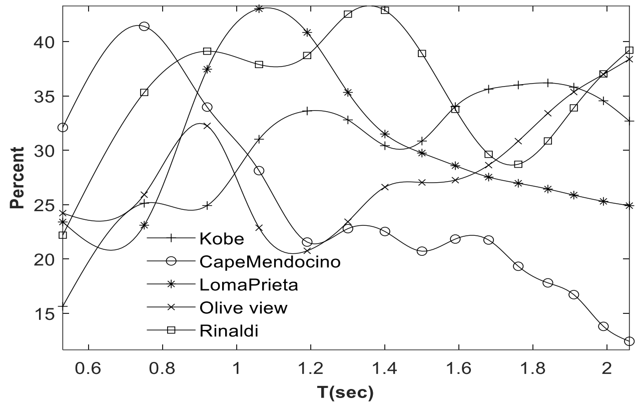


Fig. 8: The RMS displacement reduction by the fuzzy compared to passive control compared under far and near field earthquakes

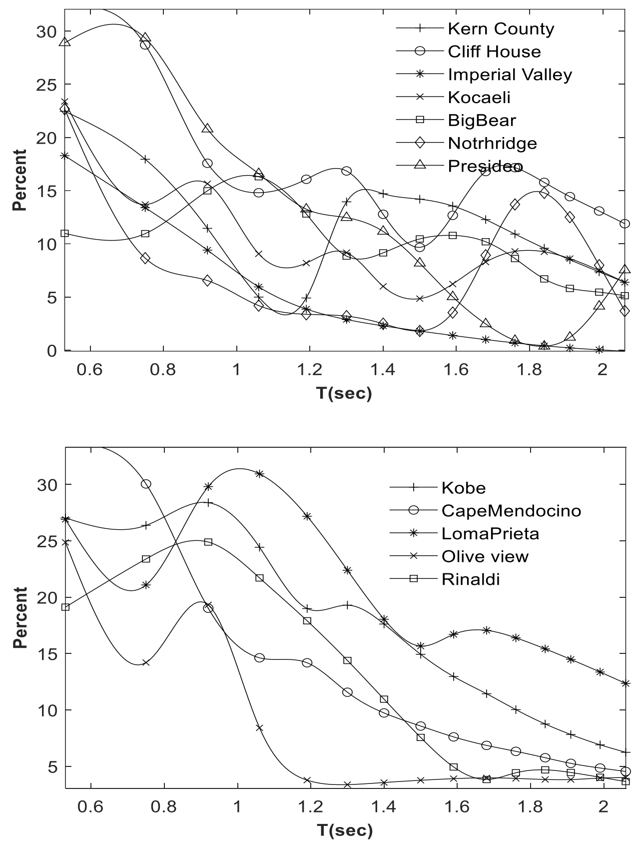
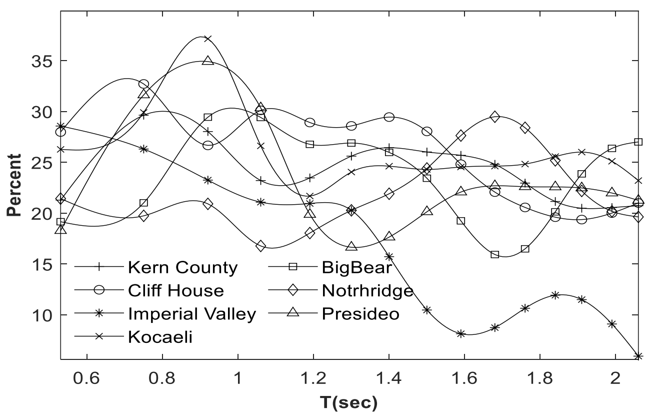


Fig. 9: The RMS acceleration reduction by the fuzzy compared to passive control under far and near field earthquakes



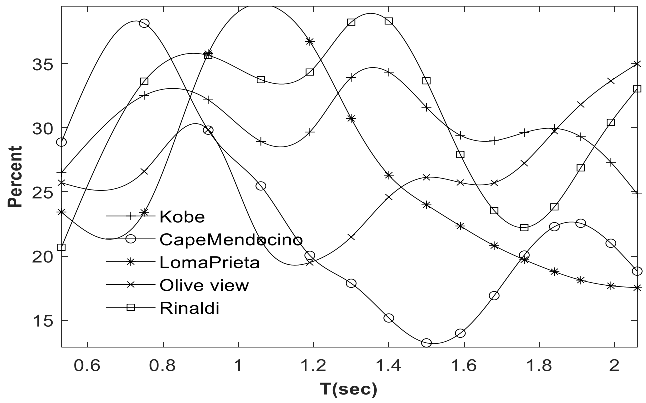


Fig. 10: The RMS base shear reduction by the fuzzy compared to passive control under far and near field earthquakes

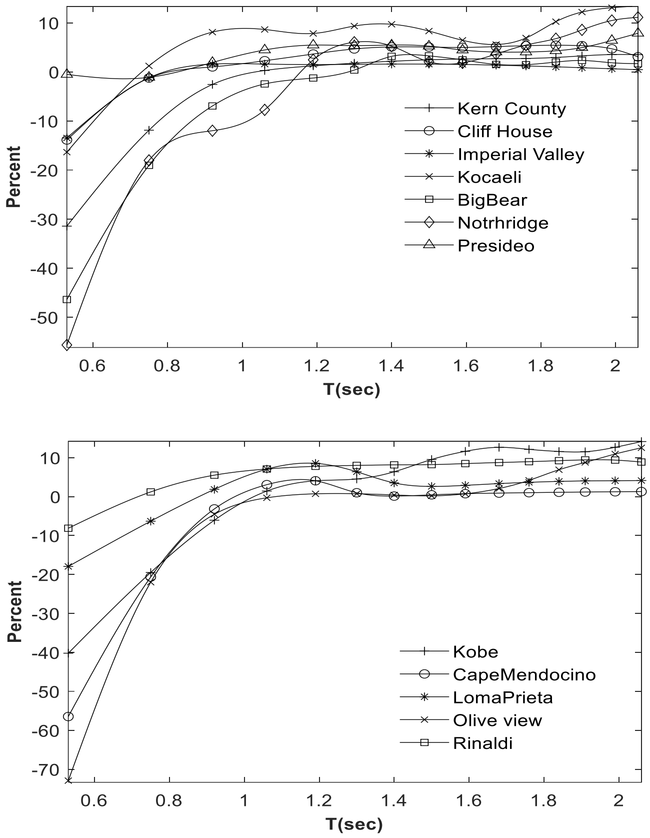


Fig. 11: The peak displacement reduction by the fuzzy compared to linear optimal control under far and near field earthquakes

highest for the Kobe earthquake, particularly in the periods between 0.53 to 0.92 seconds which are close to the fluid sloshing period, i.e., 0.67 seconds. In this period range, the optimal linear control demonstrates better performance in reducing the displacement response. Figure 13 shows that the fuzzy semi-active control is capable of achieving further reduction in structural responses, such as acceleration, for longer periods. The acceleration response reduction corresponds to improved performance criteria, especially for sensitive structures, which is an important achievement that can be obtained by the semi-active fuzzy control capabilities. In addition, from Figure 14, it is clear that the fuzzy control in its functional period range is more efficient in reducing the base shear.

Figures 12 to 14 indicate that with increasing the structural periods, the fuzzy controller does better and for the structural periods less than 1 second, the optimal linear control performance is superior. Therefore, for the structural periods less than 1 second, it is better to use the VBTLD with the linear optimal semi-active control algorithm, and for the structural periods higher than 1 second the fuzzy control is more suitable. This reason is that for the optimal linear control, solving the governing equations at each time instant increases the number of baffles' rotations and consequently the responses will be more optimal for the structural less than 1 second. In this period range, for the fuzzy control which is based on linguistic rules, the number of baffles'

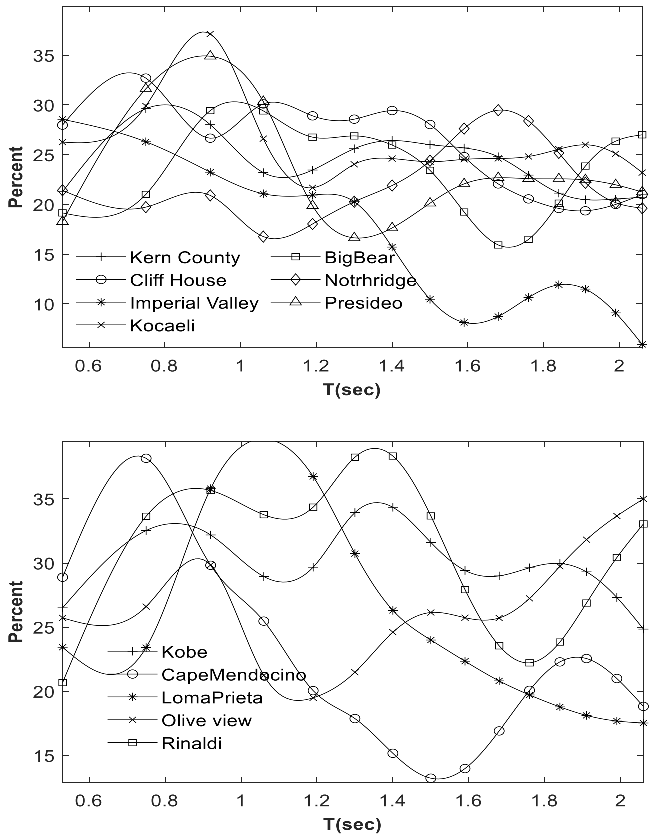


Fig. 12: The RMS displacement reduction by the fuzzy compared to linear optimal control under far and near field earthquakes

rotations is lower and the response values will be higher. The lower baffles' rotations raise the time lag at each baffle angle which lessens the control induced by the VBTLD. This can be resolved by increasing the decision-making time in the fuzzy control by defining more membership functions for the inputs and outputs of the fuzzy control, which makes the solutions more optimal. Another reason is that as in the fuzzy control, the angle change is defined based on a response range and fuzzifier functions, therefore, reducing the structural periods decreases the time for changing the angle frequently and optimally, and consequently reduces the efficiency of the fuzzy control.

Previous figures involve also the comparison between the results of near and far field earthquakes. As a general trend, the response reduction by the fuzzy control under the near field earthquakes is as well as those of the far field linear optimal control under far and near field earthquakes.

earthquakes while this is not the case for the Linear optimal control algorithm. This can be counted as a specific advantage of the VBTLD governed by the fuzzy algorithm. It is noticed that many structural control devices are not able to impose the same level of control under near and far field earthquakes and most often near field earthquakes overwhelm the performance of control devices.

The analysis of the results shows that, the fuzzy controller exhibits better behavior in earthquakes within the near-field compared to those in the far-field. However, in terms of maximum response reduction, structures with a period between 1.4 to 1.76 seconds show the best response under near-field earthquakes, while structures with a period between 1.84 to 1.99seconds show the best response under far-field earthquakes. In other words, as the structural period approaches the fluid period with closed baffles, i.e., 1.87 seconds, the fuzzy controller performs better in near-field earthquakes, whereas this trend is observable for far-field earthquakes at higher periods. From the perspective of reducing the square root of the sum of squares of the responses, the behavior of the fuzzy controller will be the best for structures with periods between 1.19 to 1.68 seconds for near-field records, and between 1.84 to 1.99 seconds for far-field records.

6. conclusion

In this study, to investigate the effectiveness of a fuzzy controller in comparison to the Linear optimal control algorithm, SDOF structural models are controlled through passive and semi-active scenarios by a variably baffled tuned liquid damper. The fuzzy and Linear optimal control algorithms are used to rotate the baffles in VBTLD through semi-active control. A set of 5 near-field and 7 far-field earthquake records have been used as excitations to evaluate the effects of the excitation type on the controllers. During semi-active control, the controller has to rotate the baffle to achieve the optimal damping ratio. The results show that the fuzzy controller can reduce both RMS and peak responses effectively. Moreover, the fuzzy controller can reduce structural responses due to near-field earthquakes as well as those of far-field earthquakes. This can be counted as a

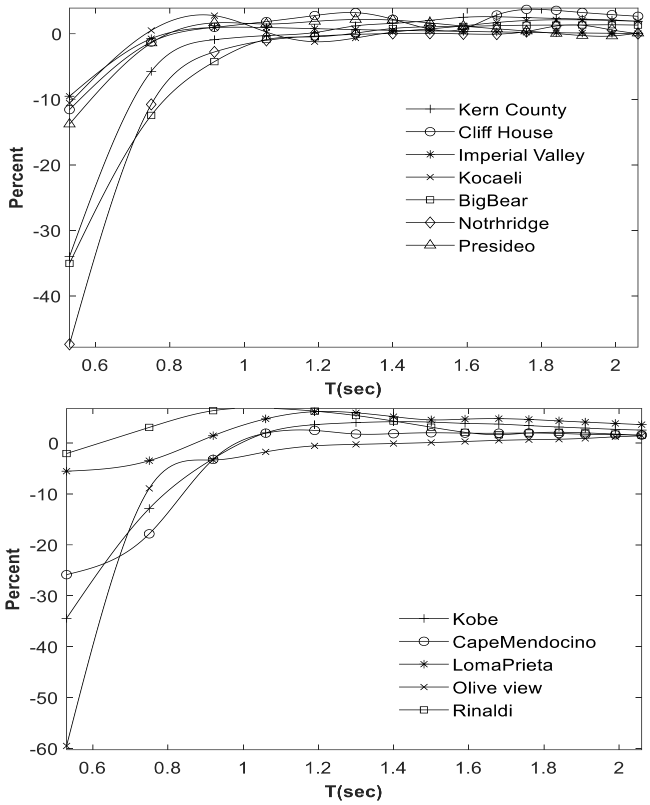


Fig. 13: The RMS acceleration reduction by the fuzzy compared to

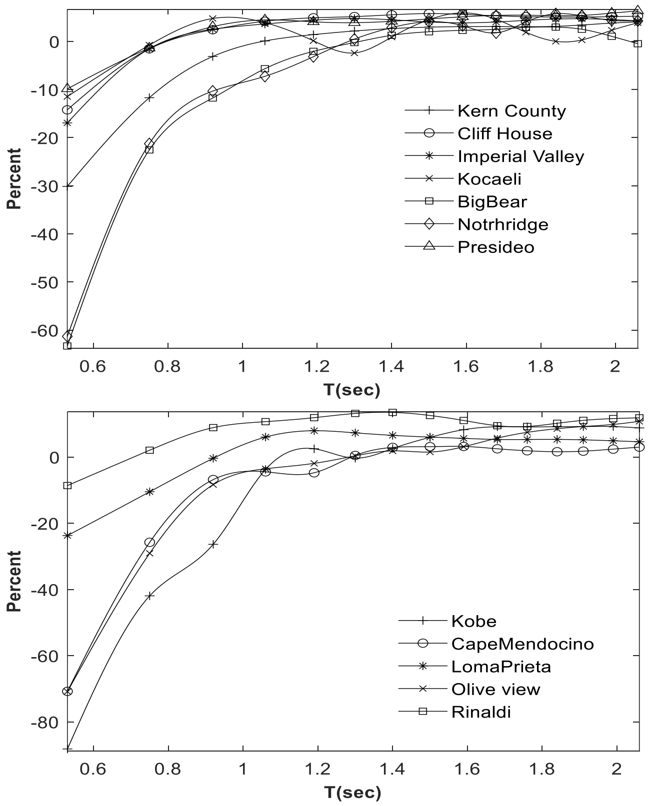


Fig. 14: The RMS base shear reduction by the fuzzy compared to linear optimal control under far and near field earthquakes

specific advantage of the VBTLD governed by the fuzzy algorithm.

In addition, the effects of the controlled structural period variations on the semi-active fuzzy control performance have been investigated under near and far-field earthquakes. The results show that for both peak and RMS responses, increasing the structural periods, and reduction in the maximum displacement, acceleration, and base shear by the semi-active fuzzy control is more than the semi-active linear optimal control.

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