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Metaheuristic based optimization of tuned mass dampers on single degree of freedom structures subjected to near fault vibrations

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Abstract

Near fault ground motions excitations have specific characteristics comparing to regular earthquake excitations. Near fault ground motions contain directivity pulses and flint steps in different directions and these excitations are the reason of more damages than regular excitations for structures. A successful method to reduce structural vibrations is the usage of tuned mass dampers. By using optimally tuned mass dampers, it will be possible to reduce vibrations resulting from earthquake excitations. In the present study, the optimization of tuned mass dampers are done for near fault excitations. During optimization, 6 different pulse like excitations are used. Three of these excitations are directivity pulses while the other ones are flint steps. The periods of excitations are 1.5s, 2.0s and 2.5s since near fault pulses have long period and big peak ground velocity around 200 m/s. The optimization objectives are related to maximum displacement of structure in time domain, the maximum stroke limitation of tuned mass damper and transfer function of the structure in frequency domain analyses. The iterative optimization process uses both time and frequency domain analyses of the structure. Three different metaheuristic algorithms are used in the methodology. These methods are harmony search algorithm, teaching learning based optimization and flower pollination algorithm which are inspired from musical performances, education process and reproduction of flowering plants, respectively. As the numerical investigation, three different single degree of freedom structures with periods 1.5s, 2.0s and 2.5s are investigated for optimum mass, period and damping ratio of a tuned mass damper positioned on the structure.

Key words

Metaheuristic algorithm, Near fault vibrations, Optimization, Tuned mass dampers

1. INTRODUCTION

The undesired responses of structures subjected to earthquake and strong winds can be reduced by using control systems. These control systems may be passive, active, semi-active or hybrid. As a passive control system, a tuned mass damper (TMD) can be used on top of the structures. There are several existing examples of using TMDs on structures. Examples include Taipei 101, Berlin TV Tower (Fig. 1), LAX theme Building and other high rise buildings, towers or bridges.

Especially, near fault ground motions are more dangerous than far fault motions because of significant impulsive motions; namely directivity pulse and flint step. These pulses have long period and big peak ground velocity (PGV). For that reason, these motions are dangerous for structures with long period. In several studies, these motions are formulized. The formulations of Makris [1] are the best equations which represent the behavior of motions. In order to use TMDs on structures in near fault regions, an optimum tuning is needed. In the documented methods, several formulations have been proposed [2-4], but these formulations may not be an exact solution for structures with inherent damping and effected by impulsive motions. For that reason, numerical algorithms are more suitable for the optimization problem. Especially, metaheuristic algorithms are effective on optimization [5-8].

Figure 1. Berlin TV Tower

In this study, the optimization of TMDs positioned on the top of single degree of freedom (sdof) structures was investigated for near fault motions. During the optimization, three directivity pulses and three flint steps (with periods 1.5s, 2.0s and 2.5s and 200m/s PGV) are considered by using the equations of Makris [1]. Three different algorithms such as harmony search (HS), flower pollination algorithm (FPA) and teaching learning based optimization (TLBO) have been used.

2. MATERIALS AND METHODS

The aim of the optimization is to find design variables such as mass (m_d), period (T_d) and damping ratio (ξ_d) of TMD by considering the optimization objectives such as related with maximum displacement ($f_1(v)$), stroke capacity of TMD ($f_2(v)$) and maximum value of acceleration transfer function ($f_3(v)$). In the methodology, the design constants, excitations and solution ranges are defined. Then, initial solution matrix (V) is constructed with p sets of solutions (v_i for the i^{th} solution) including randomly generated design variables from the defined solution range. The formulations of v_i, V, $f_1(v)$, $f_2(v)$ and $f_3(v)$ are given in Eqs.(1-5).

$$\mathrm{v}_i = \begin{Bmatrix} m_{di} \\ T_{di} \\ \xi_{di} \end{Bmatrix} \quad i = 1, \ldots., p \tag{1}$$

$$\mathrm{V} = \begin{bmatrix} \mathrm{v}_1 & \mathrm{v}_2 & \ldots & \mathrm{v}_i & \ldots & \mathrm{v}_p \end{bmatrix} \tag{2}$$

$$\mathrm{f}_1(v) = \max(|x_1 \;\; x_2 \; \ldots \; x_i \; \ldots \; x_N|) \le x_{\max} \tag{3}$$

$$\mathrm{f}_2(v) = \frac{\max(|x_d - x_N|)_{with\,TMD}}{|x_N|_{without\,TMD}} \le st\_\max \tag{4}$$

$$\mathrm{f}_3(v) = \max(|TF_N(w)|)_{with\,TMD} \le \max(|TF_N(w)|)_{without\,TMD} \tag{5}$$

In these equations, x_i are the displacement of i^{th} story; x_{max} is a user defined value which is iteratively increased (0 is the initial value in current study); x_d is the total displacement of TMD; st_max is a user defined value for stroke limitation (2 in the current study); TF_N (w) is the acceleration transfer function which uses the Laplace transforms. After the generation of initial solution matrix, new solutions are produced according to the rules of the algorithms. The main comparisons factor is $f_1(v)$, but the function; $f_2(v)$ must be provided.

HS is music based algorithm developed by Geem et al. [9]. It imitates the musical performances in a musician tries to gain admiration of audience. FPA is a nature inspired algorithm and uses four rules proposed by Yang [10] including cross pollination, self-pollination, flower constancy and switch probability. TLBO developed by Rao et al. [11] imitates two phases of education such as teacher phase and learner phase in which self-education of students is considered. The details and formulation of the algorithms can be found in Reference [8].

3. RESULTS AND DISCUSSION

Three single degree of freedom structures with 5% inherent damping and periods 1.5s, 2.0s and 2.5s are investigated for an optimum TMD. The mass of structures are taken as a symbolic value (1kg). Three different cases of maximum damping was investigated. The maximum damping ratio is 0.2, 0.3 and 0.4 for cases 1, 2 and 3, respectively while the minimum bound is 0.01. The mass ratio of TMD was searched between 1% and 10% while T_d was optimized between 0.5 and 1.5 times of the period of main structure. For the structure with 2 s period, the maximum mass ratio is taken as 20% in order to obtain an effective control. The optimum results are shown in Table 1. The objective function and maximum acceleration values are presented in Tables 2-4 for HS, FPA and TLBO algorithms. The best solutions were obtained for TLBO algorithm. For the structure with 2.0s and 2.5s period, the optimum results are the same since the optimum damping ratio of TMD is within the ranges of case 1. For the structure with 1.5s period, the results are the same for cases 2 and 3. The time history plots of top story displacements of structures are given in Figs. 2-5 for TLBO algorithm.

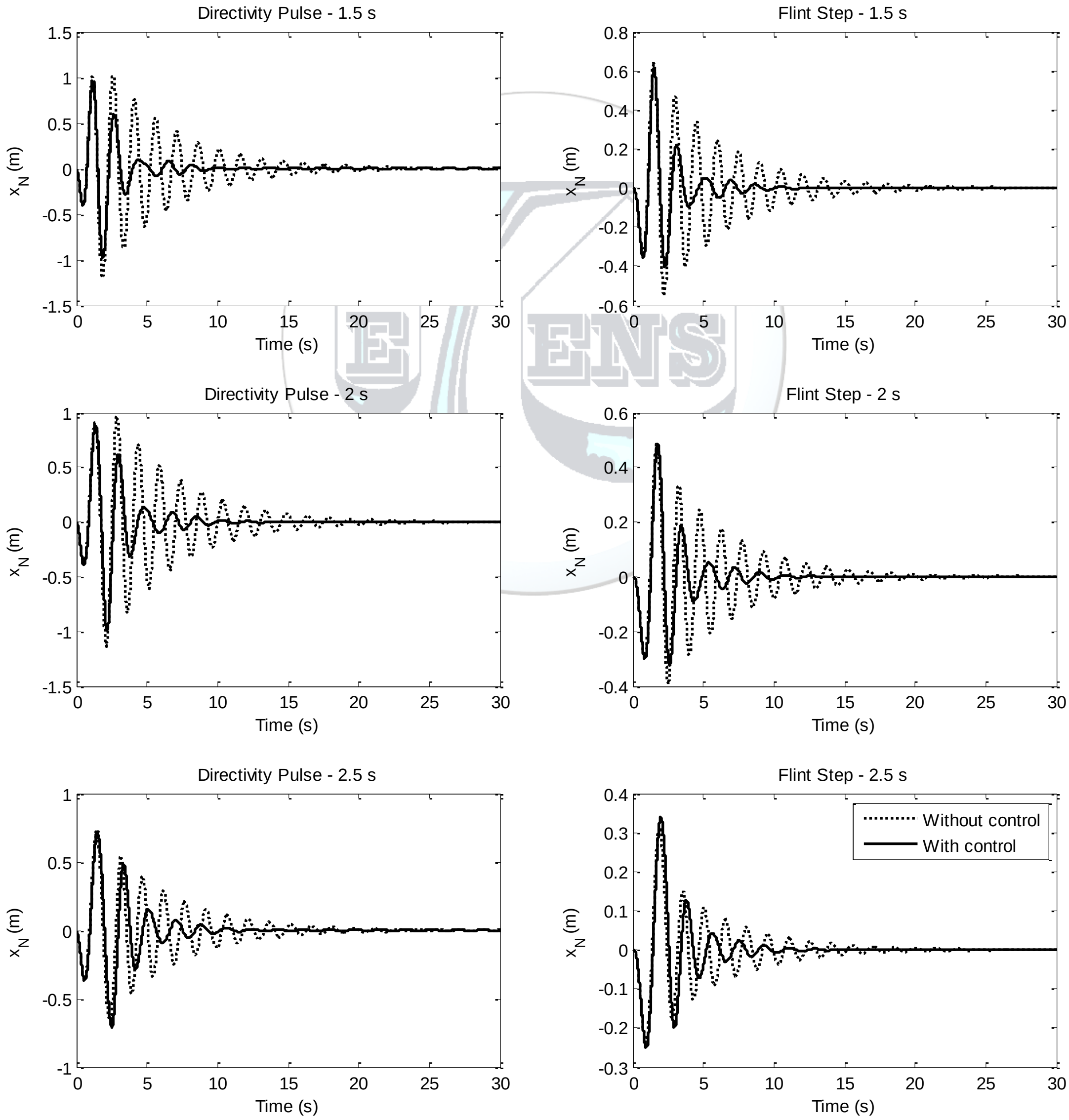

Figure 2. Time history plot for structure with 1.5s period (case 1)

Table 1. The optimum design variables

Case	Structure periods (s)	HS			FPA			TLBO		
		m_d (kg)	T_d(s)	ξ_d	m_d (kg)	T_d(s)	ξ_d	m_d (kg)	T_d(s)	ξ_d
1	1	0.100	1.597	0.190	0.100	1.653	0.200	0.100	1.653	0.200
	2	0.198	1.955	0.068	0.200	1.929	0.047	0.200	1.929	0.047
	3	0.099	2.170	0.055	0.100	2.150	0.047	0.100	2.071	0.018
2	1	0.098	1.738	0.229	0.100	1.753	0.231	0.100	1.753	0.231
	2	0.195	1.967	0.064	0.200	1.929	0.047	0.200	1.929	0.047
	3	0.099	2.070	0.024	0.100	2.071	0.018	0.100	2.071	0.018
3	1	0.099	1.729	0.227	0.100	1.753	0.231	0.100	1.753	0.231
	2	0.200	1.956	0.067	0.200	1.929	0.047	0.200	1.929	0.047
	3	0.098	2.178	0.059	0.100	2.071	0.018	0.100	2.071	0.018

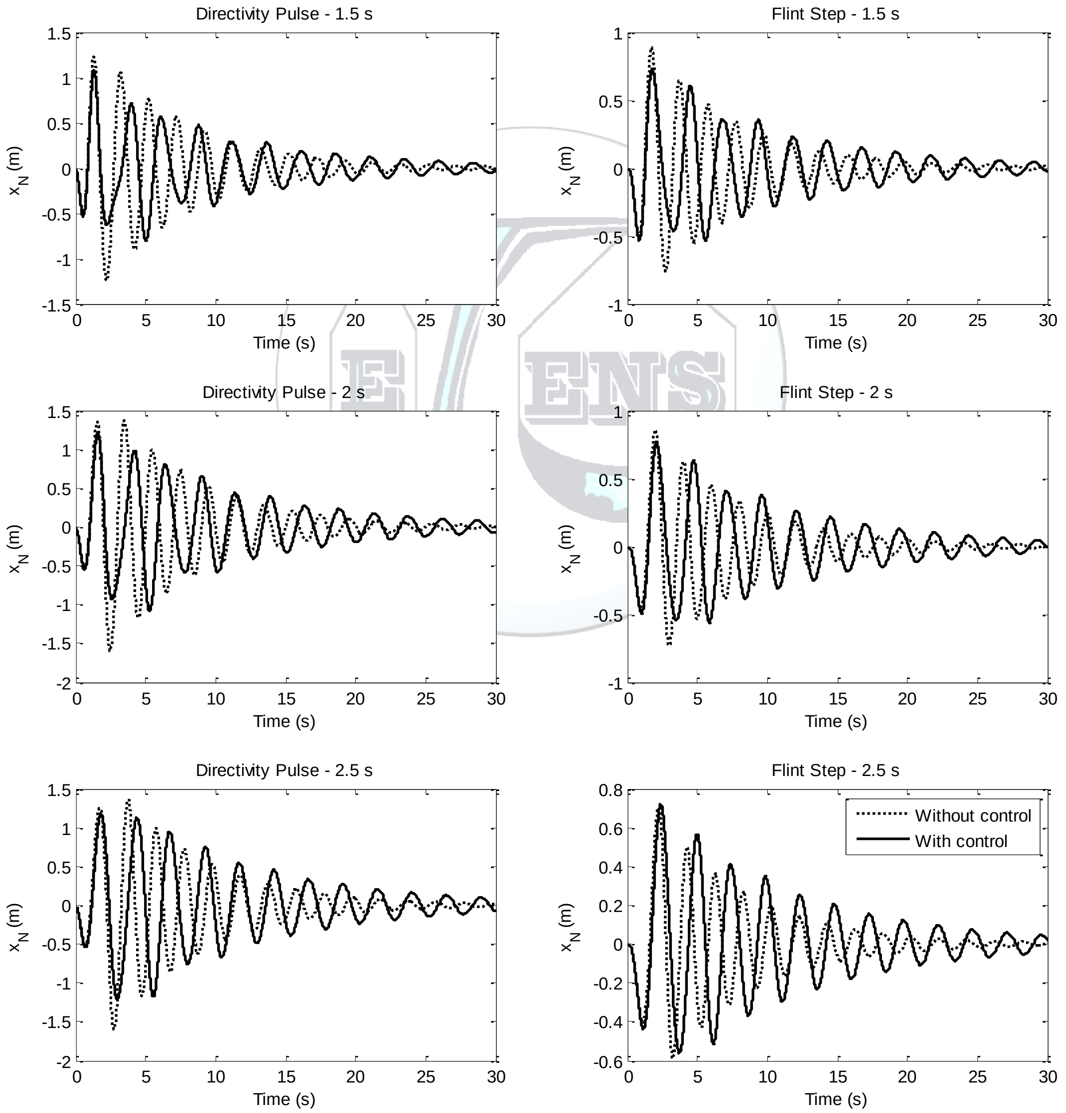

Figure 3. Time history plot for structure with 2.0s period

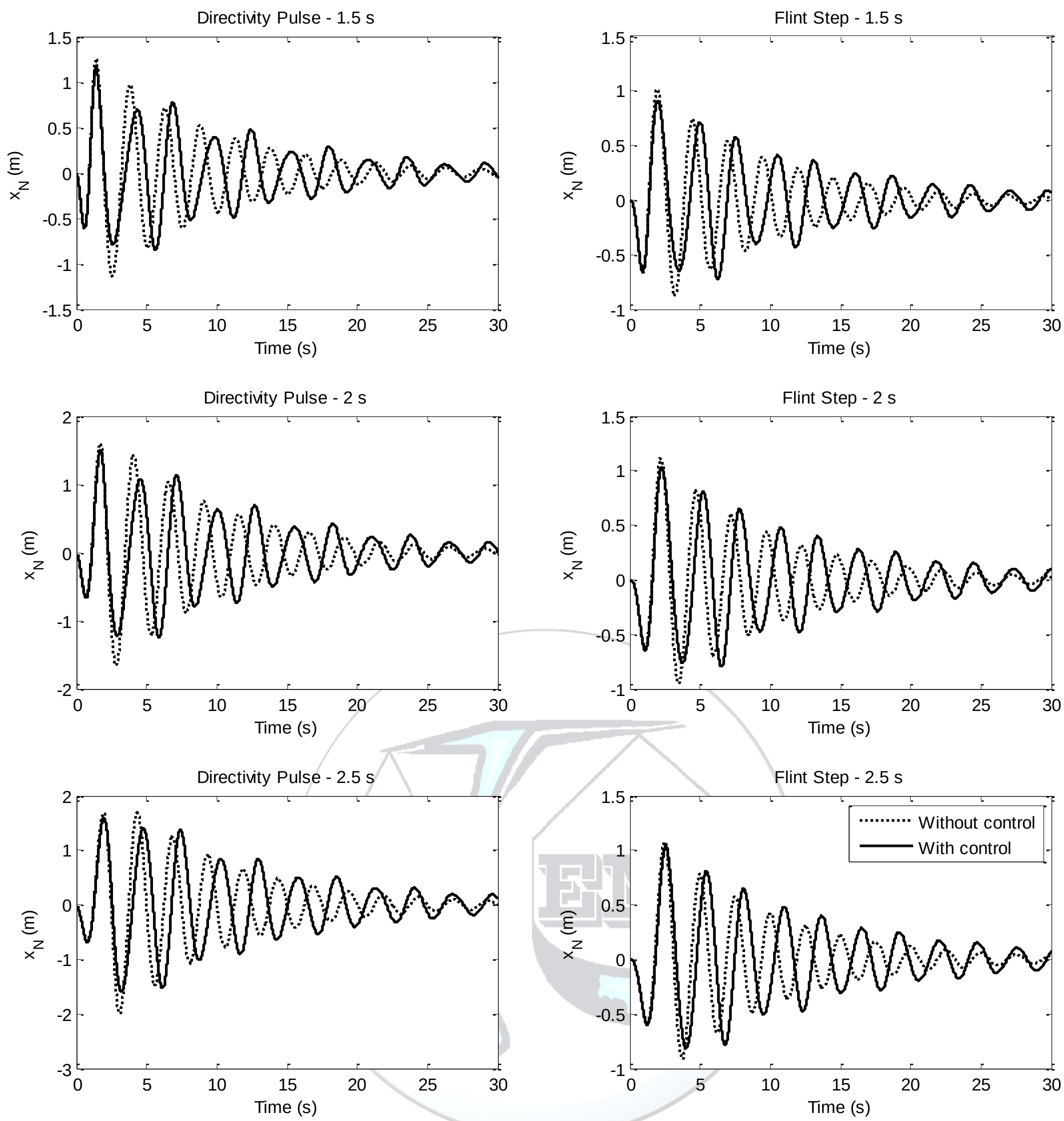

Figure 4. Time history plot for structure with 2.5s period

Table 2. The objective function values (HS)

Case	Structure periods (s)	$f_1(v)$		Maximum acceleration		$f_3(v)$		$f_2(v)$	Iteration
		With TMD	Without TMD	With TMD	Without TMD	With TMD	With TMD	Without TMD	
1	1	1.204	1.006	21.224	16.418	10.012	3.425	1.948	2184
	2	1.602	1.217	15.889	10.482	9.558	6.617	1.940	3304
	3	2.000	1.605	12.697	9.234	9.892	7.815	1.999	6373
2	1	1.204	0.998	21.224	17.033	10.012	3.882	1.994	4097
	2	1.602	1.217	15.889	10.544	9.558	6.667	1.995	1335
	3	2.000	1.604	12.697	9.109	9.892	9.760	1.967	1035
3	1	1.204	0.997	21.224	16.950	10.012	3.816	1.988	2618
	2	1.602	1.216	15.889	10.459	9.558	6.701	1.937	4062
	3	2.000	1.606	12.697	9.256	9.892	7.687	1.997	2675

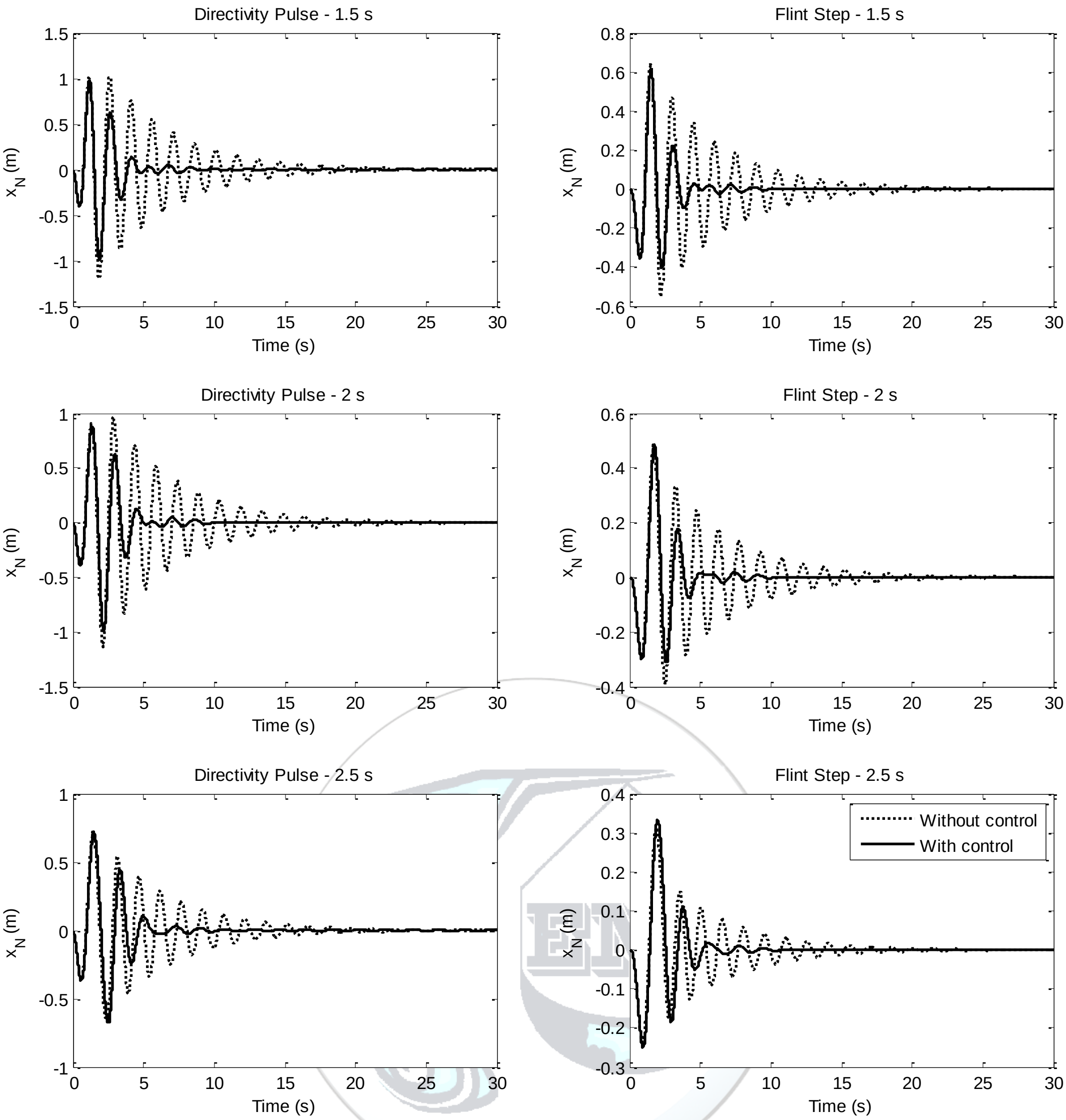

Figure 5. Time history plot for structure with 1.5s period (case 2-3)

Table 3. The objective function values (FPA)

Case	Structure periods (s)	$f_1(v)$		Maximum acceleration		$f_3(v)$		$f_2(v)$	Iteration
		With TMD	Without TMD	With TMD	Without TMD	With TMD	With TMD	Without TMD	
1	1	1.204	0.997	21.224	16.631	10.012	3.489	2.000	3465
	2	1.602	1.209	15.889	10.381	9.558	7.488	2.000	5045
	3	2.000	1.603	12.697	9.196	9.892	8.194	2.000	2620
2	1	1.204	0.994	21.224	17.014	10.012	3.909	2.000	4055
	2	1.602	1.209	15.889	10.381	9.558	7.488	2.000	4915
	3	2.000	1.601	12.697	9.085	9.892	9.892	2.000	7370
3	1	1.204	0.994	21.224	17.014	10.012	3.909	2.000	4020
	2	1.602	1.209	15.889	10.381	9.558	7.488	2.000	5090
	3	2.000	1.601	12.697	9.085	9.892	9.892	2.000	7290

Table 4. The objective function values (TLBO)

Case	Structure periods (s)	f1(v)		Maximum acceleration		f3(v)		f2(v)	Iteration
		With TMD	Without TMD	With TMD	Without TMD	With TMD	With TMD	Without TMD	
1	1	1.204	0.997	21.224	16.631	10.012	3.489	2.000	4180
	2	1.602	1.209	15.889	10.381	9.558	7.488	2.000	4480
	3	2.000	1.601	12.697	9.085	9.892	9.892	2.000	4750
2	1	1.204	0.994	21.224	17.014	10.012	3.909	2.000	4130
	2	1.602	1.209	15.889	10.381	9.558	7.488	2.000	5160
	3	2.000	1.601	12.697	9.085	9.892	9.892	2.000	6850
3	1	1.204	0.994	21.224	17.014	10.012	3.909	2.000	4010
	2	1.602	1.209	15.889	10.381	9.558	7.488	2.000	4990
	3	2.000	1.601	12.697	9.085	9.892	9.892	2.000	6850

4. CONCLUSIONS

The optimized TMDs are effective in reduction of structural displacements and accelerations. All algorithms are effective, but FPA and TLBO can find precise optimum solutions. The iteration number for the optimum values are nearly 2000 iterations. The reduction of maximum displacements are 17%, 25% and 20% for the structure with period 1.5s, 2.0s and 2.5s, respectively. For near fault motions, these values are good, but active control system may be more effective for impulsive motions. The cost, maintain, stability problem and energy consumption are big problems of the active systems comparing to passive control methods.

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