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AN OPTIMIZATION APPROACH OF TUNED MASS DAMPERS BY CONSIDERING UNCERTAIN MASS OF STRUCTURES

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Abstract. *Like all subjects in civil engineering, structural dynamics problems contain various uncertainties in design. Live loads on structures are an assumed value in the analysis. Thus, these assumptions are always effective on frequency content of the structure. Since design of structural control systems like parameter tuning of tuned mass dampers (TMD) are depended on the natural frequency of the main structure, it is not possible to obtain an exact optimum value by using a constant mass. In order to overcome this uncertainty, active control systems may be employed. Active control system may be expensive because of high monitoring and measurement costs. Thus, the mass uncertainty resulting from live loads can be considered during the numerical optimization process of passive systems. In this study, a new optimization approach considering mass uncertainty was developed by using a modified harmony search (HS) algorithm. In addition to the previous HS algorithm approach for TMDs, five structural models with different masses are analysed for all optimization steps. Three of these masses are chosen randomly within the live load range and the other two masses are taken as upper and lower bounds of the live load range. Thus, the robustness of the TMD is sustained for the changing frequency of the structure. The proposed method is demonstrated with a 10-storey shear building example. The TMD on the top of the structure was optimized by considering the changeable mass of the structure. Also, optimum TMD parameters were searched without considering the mass uncertainty. The approach is effective on finding more robust TMD parameters than the analysis conducted by using a constant mass.*

1 INTRODUCTION

The tuned mass damper (TMD) is a vibration absorber device used in mechanical systems. It contains a mass or masses in multiple tuned mass dampers (MTMD), dampers and stiffness members. Under the effect of earthquake and wind loads, TMDs has been used in high-rise structures. In order to surpass vibrations resulting from traffic, TMDs are also used in bridges.

In the tuning process of TMDs, the frequency content of the structure is the main effective parameter but the frequency (or period) of the structure may differ due to several reasons. The change of the mass of the structure directly affects the frequency of the structure. The change of the frequency of the structure may cause to detune of the TMD. For that reason, the TMDs implemented to civil structures must be robust to changing frequency of the structure. In several studies, the robustness of TMDs and MTMDs has been investigated for the change of the frequency of main structure [1-4].

The properties of the TMD can be tuned by using several approaches. For the optimum frequency and damping ratio of TMD, closed form expressions which were generally obtained for single degree of freedom (SDOF), have been proposed [5-10]. These closed form expressions are depended to a predefined mass ratio. Also, the structure must be idealised to a SDOF structure and only the critical frequency of the structure can be taken into account.

For a more realistic TMD tuning for multiple degree of freedom structures, the TMD parameters can be searched by using a numerical algorithm [7, 11-12]. Also, TMDs can be tuned by using metaheuristic algorithms. Metaheuristic algorithms employed for TMD optimization are Genetic Algorithm (GA) [13-17], Particle Swarm Optimization (PSO) [10,18], Bionic Algorithm [19] and Harmony Search [20-31].

In this study, a modified harmony search algorithm was proposed to find optimum TMD properties for structures under seismic excitations by considering the change of the live load on the structure. Different from the previous HS algorithm approaches, five structural models with different masses are analysed for all optimization steps. Three of these structures are randomly generated by using the live load range for every iteration. The other two structures are generated by using the upper (maximum live-load) and the lower (zero live-load) bounds of the live load range. Thus, the optimum TMD is robust for the changing frequency of the structure resulting from the uncertainty of live-loads. The proposed method was investigated with a 10-storey shear building example. Also, optimum TMD parameters were compared with the HS approach without live-load uncertainty consideration.

2 HARMONY SEARCH AND METHODOLOGY

Metaheuristic algorithms are inspired from natural phenomena to solve optimization problems. Harmony search (HS) imitates musical performances in solving optimization problems. In music, the goal of the musician is to gain admiration of the audience. In optimization, the aim of the process is to find the best suitable value of an objective function under different restrictions.

Three possible options can be chosen in order to gain the admiration of audience during the performance of a musician. The first option is to play any famous piece of music from their memory and this option can be formulated as the usage of harmony memory (HM) in the HS algorithm. HM is generally in matrix form in the optimization of engineering problems. In HM, design variables, which are assigned with random numbers within a selected solution range, will be stored to reach the optimum results. In generation of these variables, a special parameter; Harmony Memory Considering Rate (HMCR) is used. By using this parameter valued between 0 and 1, it is possible to choose the type of generation of new variables.

A new harmony or set of variables can be generated according to the other two option of the musician. The second option of a musician is to play something similar to a known piece in their memory. Similarly to this option, a new harmony or set of variables can be generated from the existing values stored in HM. The value of HMCR is the possibility of a harmony being selected from the existing HM. The third option is to compose a new or random note. According to this option, a new harmony can be randomly generated. Also, the adjusting of the pitches is related with the second option of musician. A parameter called Pitch Adjusting Rate (PAR) is used to adjust the local range when the HM is chosen as the source of generation. A new harmony can be searched in a smaller range around the values of HM. This range is defined by PAR which can be accepted as the ratio between the smaller range around the stored values in HM and the first selected range. By this option, it is possible to scan the values which are close to existing ones in HM in order to find more precise and optimum solutions. Also, a local optimum solution is neglected by generating the variables in different ways. The aim of the algorithm is to find best suitable values in order to minimize the objective function [32].

HS have been proposed in tuning of TMDs for harmonic loading [20, 29], SDOF idealization [21], excitations with forward directivity [22], various earthquake excitations [23-24], storey factor of the main structure [25], near and far fault ground motions [26], adjacent structures [27], irregular structures with projection in plan [28] ,preventing brittle fracture [30] and mass ratio factor [31].

In this study, HS algorithm is modified to find robust TMDs for possible frequency change of the main structure resulting from live-load uncertainty. The dynamic analysis of structure for five different live-load cases is done for all iterations inside a loop. The methodology can be explained in six steps.

i. At the beginning of the optimization process, structural data including the maximum value of live-loads, earthquake excitations, HS parameters and a possible solution range must be entered. A solution range for the possible TMD properties must be defined according to physical and economic conditions.

ii. In this step, the uncontrolled structure for two cases of live load is analysed for the future comparison of TMD controlled structure. These live-load cases are non-loaded (zero live-load) and fully loaded (maximum live load) structure.

iii. The initial harmony memory matrix is generalized with harmony vectors as many as harmony memory size (HMS). These vectors contain randomly assigned values of TMD parameters including mass, period and damping ratio.

iv. In optimization, five different cases of live loads are considered. Live-loads are randomly generated for the other three cases. In these cases, live load values are changed for every loop of the optimization process. The dynamic analyses of uncontrolled structure are done for these three live-load cases. Also, the dynamic analyses of the TMD controlled structures for all five live-loads are conducted for each set of vectors of harmony memory matrix.

v. After the step iv, a new harmony vector is formed. The special rules of the HS were used in generation. A new vector can be generated from the elements of an existing harmony vector in harmony memory (HM) or randomly from the whole solution range. Elements of a new vector are assigned within a smaller range around an existing harmony vector if a vector in the HM was chosen for the source of generation. The ratio between the smaller range and whole range is defined with the parameter called Pitch Adjusting Rate (PAR). The possibility to generate a new vector from the existing ones in HM is defined with Harmony Memory Considering Rate (HMCR). The program randomly chooses an existing vector but the best vector has more possibility than others. When generating a new vector from the HM, the probability to select the best vector is defined with Best Harmony Memory Considering Rate (BHMCR).

The best vector is selected according to a parameter called Best Solution (BS), which is the sum of the ratios of first storey peak displacements (DR) and peak values of first storey acceleration transfer function (TFR) at the first natural frequency for all live-load cases. If the newly generated vector is better than the existing worst ones, it is replaced with the worst one. By this elimination, all results of different live-load cases in addition to first storey acceleration transfer function are taken into consideration in the optimization process.

vi. Stopping criterion must be checked. The ratio of the peak first storey displacements of the structure with and without TMD must be less than a user defined ratio value for all cases of live loads. The program can automatically increase this value after several iterations if a solution cannot be found within the solution range.

If the criterion is not satisfied, the process continue from step iv by generation three new live-load cases. The flowchart of the optimization process can be seen in Figure 1.

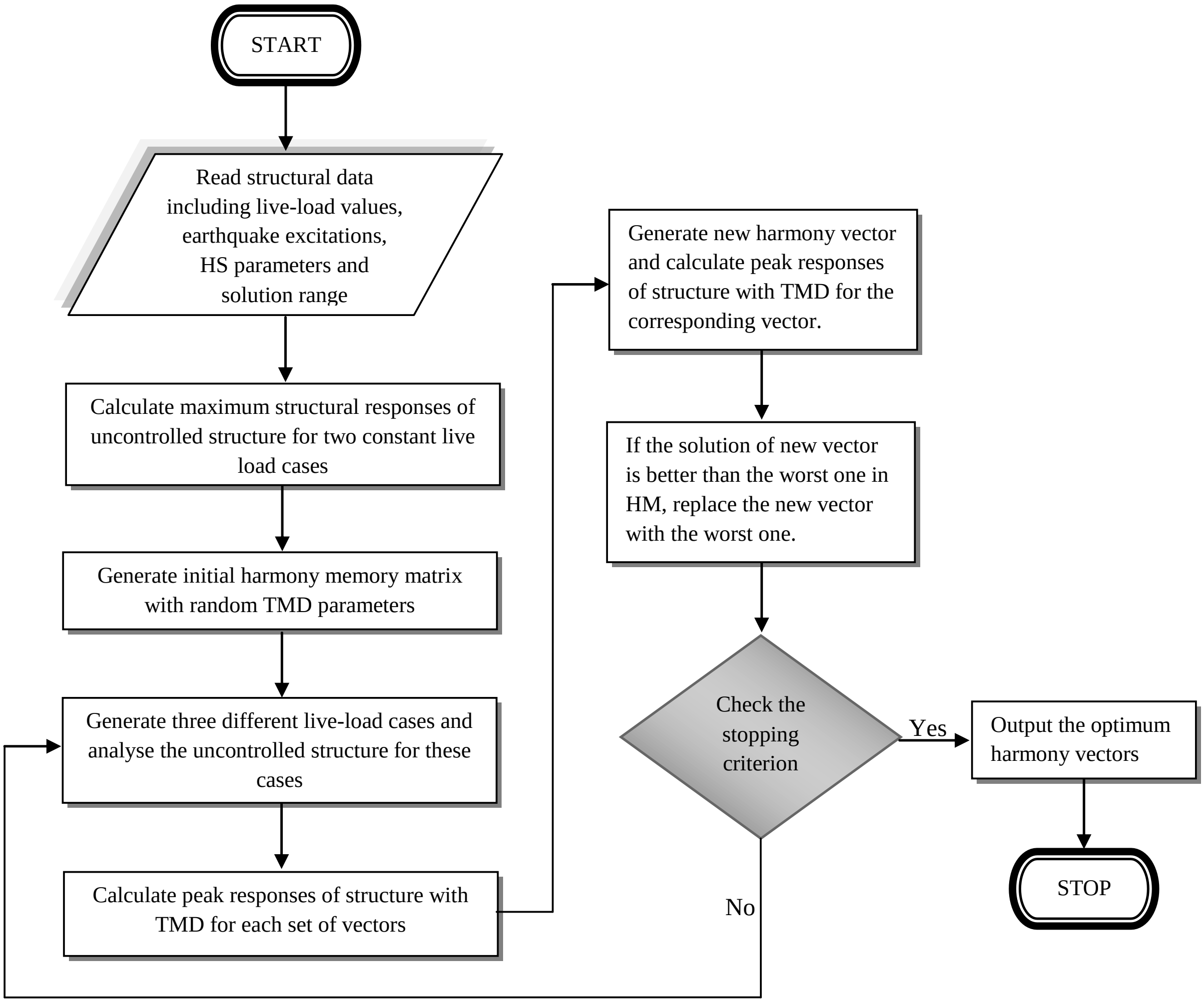

Figure 1: The flowchart of the optimization process.

3 NUMERICAL EXMAPLE

The approach was applied to a 10-storey multiple degrees of freedom shear structure. A TMD, which is positioned on the top of the structure, was optimized. A storey of the structure has the same mass excluding live loads (360 t), damping coefficient (6.2 MN s/m) and stiffness (650 MN/m) [33]. The maximum live-load is 200 t for a storey. According to the live-load, the period of the structure is between 1 s and 1.23 s. The earthquake records used in the optimization of TMDs are given in Table 1.

Earthquake	Date	Station	Component	PGA (g)
Kobe	1995	0 KJMA	KJM000	0.821
Imperial Valley	1940	117 El Centro	I-ELC180	0.313
Erzincan	1992	95 Erzincan	ERZ-NS	0.515
Kern Country	1952	1095 Taft	TAFT111	0.178
Northridge	1994	24514 Sylmar	SYL360	0.843
Loma Prieta	1989	16 LGPC	LGP000	0.563

Table 1: Earthquake records.

HS parameters were taken as 5, 0.5, 0.5 and 0.1 for HMS, HMCR, BHMCR and PAR, respectively. The solution range for the period of the TMD is between 0.8 and 1.2 times of the natural period of the main structure loaded with maximum live-load (1.18 s). The damping ratio range was taken between 5% and 20%. Two different mass ratio ranges were used. The lower limit of the mass ratio is 1% and the upper limits are 2.5% (Case 1) and 3% (Case 2).

The optimum results were compared with the optimum results obtained by without considering live-load uncertainty. In the optimization without live-load uncertainty, the TMD is only tuned according to a single live-load value. This value is taken as 30% of the maximum load as defined in Turkish Earthquake Code (TEC2007) [34]. The upper and lower limits of the mass ratio were configured to equalize the maximum and minimum mass of the TMD for the optimization process with and without live-load uncertainty.

The optimum TMD parameters (m_{TMD}= TMD mass, T_{TMD}= TMD period, ξ_{TMD}= TMD damping ratio) are given in Table 2 for the analyses with (with con. LL uncer.) and without (without con. LL uncer.) considering live-load uncertainty.

	with con. LL uncer.			without con. LL uncer.		
Case	m_{TMD}	T_{TMD}	ξ_{TMD}	m_{TMD}	T_{TMD}	ξ_{TMD}
1	140 t	1.176 s	0.1996	136 t	1.121 s	0.1976
2	168 t	1.171 s	0.1964	166 t	1.117 s	0.1995

Table 2: Optimum TMD parameters.

The optimum results were obtained for the live-load values given in Table 3. The first five live-load combination was used in the optimization considering uncertainty. The sixth one is the constant live-load values with 30% live-load for each storey.

Storey	live-load1 (t)	live-load2 (t)	live-load3 (t)		live-load4 (t)		live-load5 (t)		live-load6 (t)
			Case1	Case 2	Case1	Case 2	Case1	Case 2	
1	0	200	76.0	11.8	0.6	117.5	33.0	46.2	60
2	0	200	158.8	199.4	25.7	50.6	162.1	44.8	60
3	0	200	32.0	152.3	20.0	4.3	74.3	36.0	60
4	0	200	52.1	8.3	198.4	5.2	98.4	188.1	60
5	0	200	10.7	171.3	181.8	146.8	197.7	15.0	60
6	0	200	119.4	185.4	13.2	165.4	116.9	112.2	60
7	0	200	149.6	3.9	172.0	63.9	106.5	21.7	60
8	0	200	149.6	6.0	88.5	55.4	179.2	124.5	60
9	0	200	94.3	129.1	71.6	70.5	5.1	63.5	60
10	0	200	182.6	177.8	77.4	16.2	16.1	137.0	60

Table 3: Live-load combinations.

The ratios of first storey peak displacements (DR) and peak values of first storey acceleration transfer function (TFR) at the first natural frequency were given in Table 4.

	with live-load uncertainty				without live-load uncertainty			
	CASE 1		CASE 2		CASE 1		CASE 2	
live-load	DR	TFR	DR	TFR	DR	TFR	DR	TFR
1	0.7759	0.0918	0.7577	0.0739	0.7609	0.0966	0.7418	0.0791
2	0.8086	0.1201	0.8043	0.1116	0.8469	0.1423	0.8418	0.1330
3	0.7854	0.0892	0.7771	0.0773	0.7984	0.1043	0.7842	0.0925
4	0.7746	0.0909	0.7668	0.0832	0.7823	0.0988	0.7632	0.0803
5	0.7793	0.0927	0.7718	0.0776	0.7840	0.0970	0.7750	0.0864
6	0.7800	0.0960	0.7696	0.0821	0.7761	0.0860	0.7650	0.0765

Table 4: DR and TFR values obtained for optimum results.

According to the results given in Table 4, the best reduction is occurred for the structure without live-load. Also, the lowest reduction is seen for the structure loaded with maximum live-load. The approach considering live-load uncertainty is effective to reduce maximum first storey displacement of fully loaded structure with 19.5% approximately. This reduction is approximately 15.5% for the approach without considering mass uncertainty. Also, the proposed approach is more effective than the compared approach for random live-load combinations while the compared approach is more effective for the structure loaded with 0% and 30% live-load. Northridge excitation is the most critical earthquake for the reduction percentage of the first storey displacement.

For all live load combinations, time-history plots of first storey displacements (x_1) under Northridge excitation for Case 1 considering live-load uncertainty is given in Figure 2.

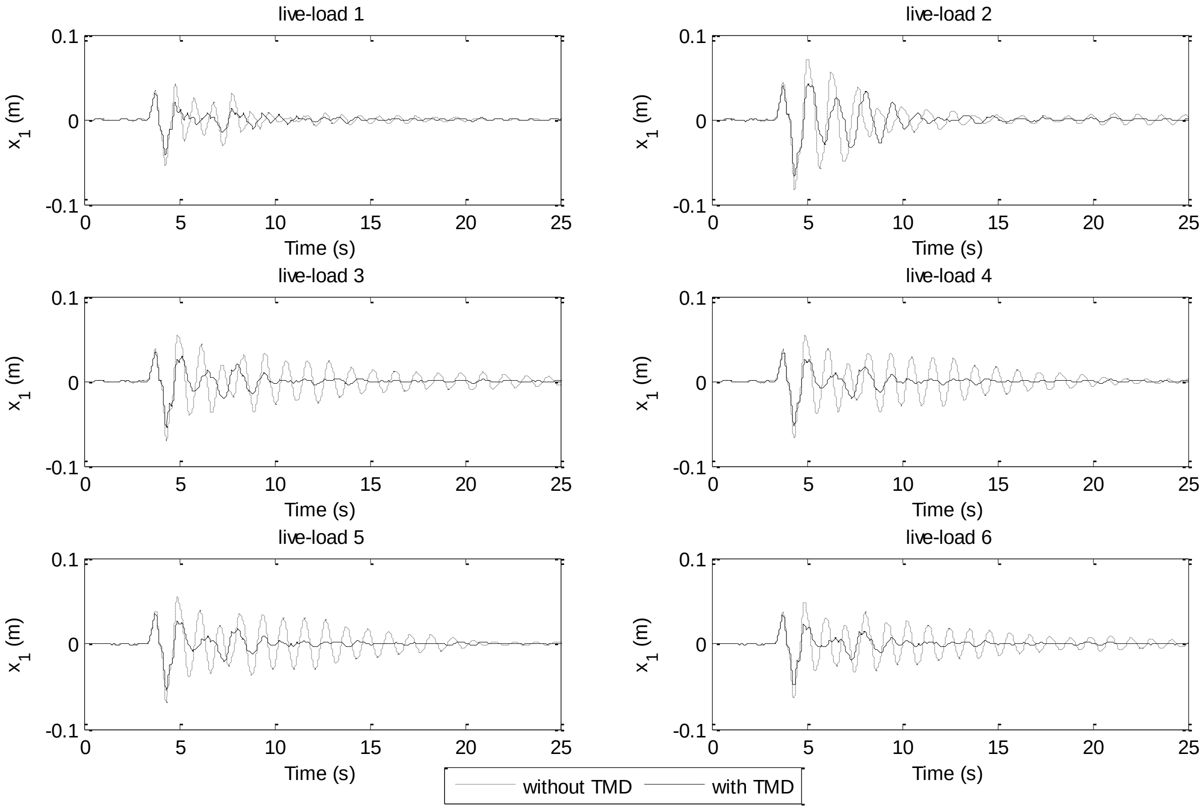

Figure 2: Time-history plots of first storey displacements under Northridge excitation (Case 1 - with live-load uncertainty).

The time-history plots of first storey displacements under Northridge excitation for Case 2 are given in Figure 3. For both cases, TMDs are effective to reduce peak displacements and to obtain a rapid steady state response for all loading combinations.

4 CONCLUSIONS

The frequency content of the structures is depended to external conditions like earthquakes and live-loads. In design, a possible value of live loads is assumed in structures according to several design codes. In reality, live-loads are changeable by time. Also, for the dynamic analyses of structures, a constant mass must be taken in order find the frequency content of the structure. According to frequency content, control devices like TMDs are tuned and optimized. In this study, tuned mass damper implemented on the top of a structure is optimized by using a modified HS approach considering live-load uncertainty. The proposed approach is effective on finding robust TMD parameters for the changing frequency of the structure between 1s and 1.23 s.

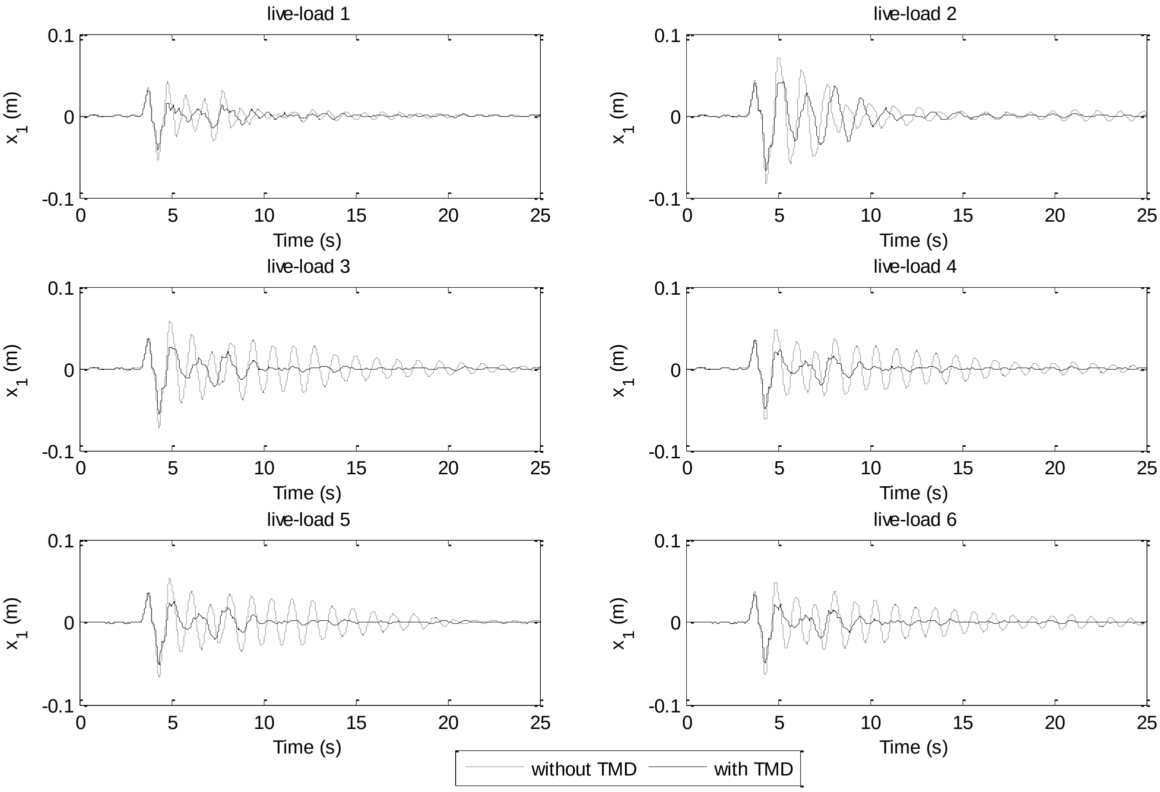

Figure 3: Time-history plots of first storey displacements under Northridge excitation (Case 2 - with live-load uncertainty).

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