Optimum Design of Tuned Mass Dampers for Adjacent Structures via Flower Pollination Algorithm

Sinan Melih Nigdeli[1], Gebrail Bekdaş[1] and Xin-She Yang[2]

[1]Department of Civil Engineering, Istanbul University-Cerrahpaşa, Avcılar/Istanbul/Turkey
melihnig@istanbul.edu.tr, bekdas@istanbul.edu.tr

[2] Department of Design Engineering & Maths, Middlesex University, Middlesex/London/UK
x.yang@mdx.ac.uk

Abstract. It is a very known issue that tuned mass dampers (TMDs) on an effective system for structures subjected to earthquake excitations. TMDs can be also used as a protective system for adjacent structures that may pound to each other. With a suitable optimization methodology, it is possible to find an optimally tuned TMD that is effective in reducing the responses of structure with an additional protective feature that reduces the amount of required seismic gap between adjacent structures by using an objective function. This function considers the displacement of structures with respect to each other. As the optimization methodology, the flower pollination algorithm (FPA) is used in finding the optimum parameters of TMDs of both structures. The method was evaluated on two 10-story adjacent structures and the optimum results were compared with harmony search (HS) based methodology.

Keywords: Adjacent Buildings, Optimization, Control, Tuned Mass Dampers, Flower Pollination Algorithm.

1 Introduction

During the major strong earthquakes, one of the reasons for damage of structures is the pounding of building blocks. These damages may lead to termination of the use buildings by the occurred high damages that can be retrofitted or not. The worst-case that are observed in the historical earthquakes is the collapse of the building with fatalities. To avoid this danger, the regular way to protect the adjacent structures is to provide a seismic gap. Sometimes, this seismic gap cannot be provided in the required amount, or the effect that occurred in structures during earthquakes may be bigger than the expected amount.

According to Jeng and Tzeng [1], five major types of pounding existence as follows:

- Mid-column pounding
- Heavier adjacent building pounding
- Taller adjacent building pounding

ICCS Camera Ready Version 2021
To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77970-2_9

- Eccentric pounding
- End building pounding

Mid-column pounding is the most seen case in the collapse of the structures after earthquakes. It is the pounding of the heavy story level of a building to the mid-point of the columns of the other building. The damage of slender columns is dangerous for the total collapse of the structures.

Heavier adjacent pounding is dangerous due to a heavy structure collide with a lighter adjacent one. It is a majorly seen type since the behavior of heavy and light structures can differ during earthquakes because of very different value of critical periods. The same behavior difference can be the same for one high-rise and low-rise adjacent building. This situation is called taller adjacent building pounding.

Due to torsional irregularity of structure, eccentric pounding may occur in a side of the structure due to the increasing effect of displacement of the corner points.

In the end, building pounding, series of structure blocks act as a series of colliding pendulums.

To prevent pounding several control methods have been proposed. These structural control types are passive, active, and semi-active or hybrid systems. As a passive system, nonlinear hysteric damper interconnecting adjacent structure [2], bumper-type collision shear walls [3], viscoelastic dampers connecting the adjacent structures [4], rubber shock absorbers [5], viscous damper with different retrofit schemes [6], passive damper [7] mass dampers [9] were presented. As semi-active systems, Magnetorheological (MR) damper [10-11] and variable damping semi-active (VSDA) systems [12] were used. Kim and Kang developed a hybrid system by controlling the damping force of MR dampers [13]. The proposed active control system for the adjacent structures includes hydraulics actuators using linear quadratic Gaussian (LQG) controllers by Xu and Zhang [14] active control system using preference-based optimum design approach [15].

As a recent development, Guenidi et al. [16] proposed shared TMDs that are using passive or MR dampers as elements for connection to adjacent structures. Wu et al. [17] investigated adjacent inelastic reinforced concrete frame structures connected with viscous fluid dampers. Baili et al. [18] connected adjacent single degree of freedom (SDOF) systems with spring-dashpot-inerter control systems. Azimi and Yeznabad [19] investigated semi-active MR dampers for adjacent structures by proposing a swarm-baed parallel control algorithm. Also, Lin et al [20] proposed a modified crow search algorithm-based fuzzy control for adjacent structures using MR dampers. Nigdeli and Bekdaş employed a hybrid harmony search algorithm to optimize adjacent structures using a vibration absorber system [21]. Wang et al. [22] proposed to link adjacent structures via tuned liquid column damper-inerter (TLCDI).

The optimization of all control systems is needed for the effective performance of the system. Especially, the systems for control of adjacent structure involves the consideration of the behavior of all structure or a complex model of linked structures. In that case, it will be a complex problem that can be solved via metaheuristic algorithms. For that reason, the seismic gap between these structures can be reduced by the use of optimum TMDs for both structures.

ICCS Camera Ready Version 2021
To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77970-2_9

In this study, the flower pollination algorithm developed by Yang [23] is proposed for this control problem in the optimization of TMDs. In the optimization methodology, time-domain solutions are evaluated to consider an objective function that is the relative displacement of structure with respect to the other one. The methodology is applied to 10-story adjacent structures that have different behavior. The results of the method are compared with the harmony search-based methodology that is also applied for the same models by using the same numerical analysis criteria.

2 The optimization methodology

For structures under seismic excitations, it is needed to develop numerical iterations for the time-history analysis. Due to that, it is not possible to develop an equation of the response of the structure. The only and detailed way is to solve sets of coupled differential equations related to the motion of the structure that is also subjected to a ground acceleration due to an earthquake. The content of this excitation also includes different frequencies. Another factor is also related to the damping of the structure, and it is a restriction in finding a simple equation. With the increase of the degree of structural system, it is harder to solve the coupled equations. Since it is not possible to derive a simple equation, the case of finding the minimum of this equation for a set of design variables is not possible.

In the case of the present paper, two adjacent buildings will be investigated to add TMDs to the structure. By this passive control system, the objective is to reduce the maximum displacement of the structure with respect to the other. Via this reduction, the pounding of the structure blocks will be prevented, since the amount of the required seismic gap reduces. The objective function (f(X)) that is depending on the analysis results by considering the properties of TMDs as the design variables is shown in Eq. 1. From x_1 to x_N (x_1 to x_N for structure 2), the displacements of the stories of structure 1are shown.

$$f(X)=\max(|[x_1\ x_2\ \ldots\ x_N]^T-[\mathit{x}_1\ \ \mathit{x}_2\ \ldots\ \mathit{x}_N\ ]^T|) \tag{1}$$

The set of design variables are shown as Eq. 2 for i^th individual of the population (p) used in the optimization.

$$X_i=\{m_d\ T_d\ \xi_d\ \mathit{m}_d\ \mathit{T}_d\ \mathit{\xi}_d\ \}\quad i=1\,\mathrm{to}\,p \tag{2}$$

The case study of adjacent structures with TMDs is shown in Fig.1. In table 1, the design constraints and variables related to the problem are listed. It must be noted that the italic symbols represent the response of the second structure.

Instead of stiffness (k_d, k_d) and damping coefficient (c_d, c_d), the periods (T_d, T_d) and damping ratios (ξ_d, $\mathit{\xi}_d$) of TMDs are respectively defined as Eq. 3 and Eq. 4 are considered as the design variables of the problem.

ICCS Camera Ready Version 2021
To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77970-2_9

$$T_d = 2\pi\sqrt{\frac{m_d}{k_d}} \tag{3}$$

$$\xi_d = \frac{c_d}{2m_d\sqrt{\frac{k_d}{m_d}}} \tag{4}$$

In the optimization process, after the definition of the design constants and range of design variables, the initial solution matrix including sets of design variables is randomly generated. Afterward, the analysis of adjacent structures is done using Matlab with Simulink [24] to find the value of f(X) for all sets of variables for future comparison with the updated design variables by using algorithm rules.

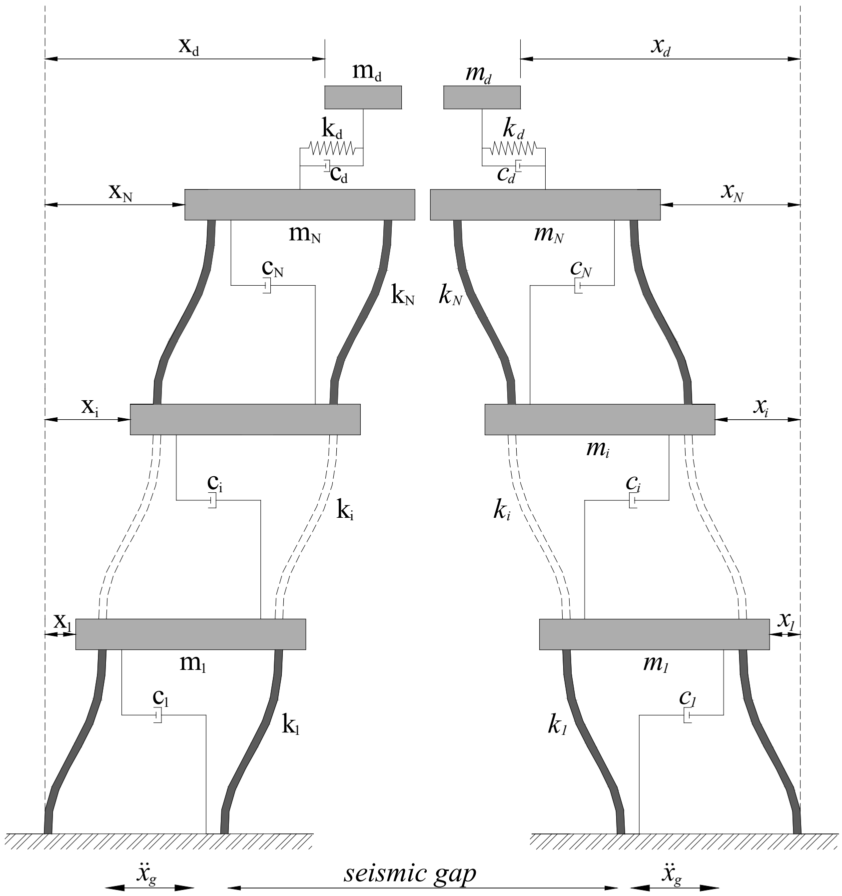

Fig 1. Adjacent structures with TMDs

DOI: 10.1007/978-3-030-77970-2_9

Table 1. The design constants and design variables ranges

Symbol	Type	Definition
m_i	Constant	Mass of the i^{th} story for structure 1 (i=1 to N)
c_i	Constant	Stiffness of the i^{th} story for structure 1 (i=1 to N)
k_i	Constant	Damping coefficient of the i^{th} story for structure 1 (i=1 to N)
m_i	Constant	Mass of the i^{th} story for structure 2 (i=1 to N)
c_i	Constant	Stiffness of the i^{th} story for structure 2 (i=1 to N)
k_i	Constant	Damping coefficient of the i^{th} story for structure 2 (i=1 to N)
$\ddot{x}_g$	Constant	Ground acceleration (defined as data)
m_d	Variable	Mass of TMD on the structure 1
T_d	Variable	Periods of TMD on the structure 1
ξ_d	Variable	Damping ratio of TMD on the structure 1
m_d	Variable	Mass of TMD on the structure 2
T_d	Variable	Periods of TMD on the structure 2
$\mathit{\xi}_d$	Variable	Damping ratio of TMD on the structure 2

For the analysis, the equations of motion of N-story adjacent structures with TMDs on the top are written as Eq. 5.

$$\begin{aligned} &\mathrm{M}\ddot{\mathrm{x}} + \mathrm{C}\dot{\mathrm{x}} + \mathrm{K}\mathrm{x} = -\mathrm{M}\{1\}\ddot{\mathrm{x}}_g \\ &M\ddot{x} + C\dot{x} + Kx = -M\{1\}\ddot{x}_g(t) \end{aligned} \tag{5}$$

M, C and K (*M*, *C* and *K* for structure 2) are respectively mass (Eq. 6), damping (Eq. 7) and stiffness (Eq. 8) matrices. The vector of structural displacements (Eq. 9) is shown with x and *x* for structures 1 and 2, respectively. {1} represents a vector of ones.

$$\mathrm{M}=\mathrm{diag}[\mathrm{m}_1\ \mathrm{m}_2\ \ldots\ \mathrm{m}_N\ \mathrm{m}_d]\quad M=\mathrm{diag}[m_1\ m_2\ \ldots\ m_N\ m_d] \tag{6}$$

$$\mathrm{C} = \begin{bmatrix} (\mathrm{c}_1+\mathrm{c}_2) & -\mathrm{c}_2 & & & & & \\ -\mathrm{c}_2 & (\mathrm{c}_2+\mathrm{c}_3) & -\mathrm{c}_3 & & & & \\ & . & . & & & & \\ & . & . & . & & & \\ & & . & . & . & & \\ & & & & -\mathrm{c}_N & (\mathrm{c}_N+\mathrm{c}_d) & -\mathrm{c}_d \\ & & & & & -\mathrm{c}_d & \mathrm{c}_d \end{bmatrix}$$

$$C = \begin{bmatrix} (c_1+c_2) & -c_2 & & & & & \\ -c_2 & (c_2+c_3) & -c_3 & & & & \\ & . & . & & & & \\ & . & . & . & & & \\ & & . & . & . & & \\ & & & & -c_N & (c_N+c_d) & -c_d \\ & & & & & -c_d & c_d \end{bmatrix} \tag{7}$$

ICCS Camera Ready Version 2021
To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77970-2_9

$$K = \begin{bmatrix} (k_1 + k_2) & -k_2 & & & & & \\ -k_2 & (k_2 + k_3) & -k_3 & & & & \\ & . & . & & & & \\ & . & . & . & & & \\ & & . & . & . & & \\ & & & & -k_N & (k_N + k_d) & -k_d \\ & & & & & -k_d & k_d \end{bmatrix} \tag{8}$$

$$K = \begin{bmatrix} (k_1 + k_2) & -k_2 & & & & & \\ -k_2 & (k_2 + k_3) & -k_3 & & & & \\ & . & . & & & & \\ & . & . & . & & & \\ & & . & . & . & & \\ & & & & -k_N & (k_N + k_d) & -k_d \\ & & & & & -k_d & k_d \end{bmatrix}$$

$$x = [x_1 \; x_2 \ldots x_N \; x_d]^T \tag{9}$$

$$x = [x_1 \; x_2 \ldots x_N \; x_d]^T$$

After the generation of an initial solution matrix, the iterative optimization process starts. FPA is a nature-inspired metaheuristic algorithm that imitates the process of pollen transfer for flowering plants. FPA includes two optimization types that are global and local optimization. These optimization phases are chosen according to a switch probability (sp).

The main idea of the pollination process of flowers to be used as an optimization algorithm is associated with flower constancy. It is the tendency of a specific pollinator to a specific flower type. Each solution of design variables is associated as a flower.

As a type of optimization phase, global optimization or namely, global pollination involves two types of pollination. These are biotic pollination and cross-pollination. In biotic pollination, the carry process of pollens is done via pollinators that are living organisms like bees, insects, etc. Cross-pollination is the pollination of different plants. Since these two types involve different plants and the pollen transfer is done in long distances, it is named global pollination. It is formulated as Eq. 10.

$$X_i^{t+1} = X_i^t + L(X_i^t - g^*) \tag{10}$$

In Eq. 10, a Levy distribution (L) shows the effect of the random flight of pollinators. Also, the best existing solution (g^*) is used in the generation of a new solution (X_i^{t+1} for i^{th} individual and $t+1^{th}$ iteration) using the existing one (X_i^t).

In local optimization or namely local pollination, self-pollination and abiotic pollination are imitated. In self-pollination, the reproduction is done for the same plant as self-fertilization. In abiotic pollination, the carry of pollens is done by natural events like winds, diffusion in water, etc. It is formulated as Eq. 11.

$$X_i^{t+1} = X_i^t + \varepsilon(X_j^t - X_k^t) \tag{11}$$

ICCS Camera Ready Version 2021
To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77970-2_9

Since it is local pollination, two existing solutions (X_j^t and X_k^t) are used with a linear distribution (ε) taken as a random number between 0 and 1.

The newly generated solution is checked for the objective function value, and the new ones are selected instead of the existing ones if the value of f(X) is smaller than the existing ones for the modified new solutions. This process continues for several iterations.

3 The numerical example

As the numerical validation of the method, two adjacent structure with ten stories were investigated. The properties of these structures are listed in Table 2. The first structure has 1 s critical period, and it has the same properties for all stories. The second structure has 2 s critical period, and it has different properties for all stories. The first structure has heavier masses than the second one. Also, the first structure is more rigid comparing to the second structure.

During the optimization, six different earthquake records shown in Table 3 are used. The excitation with the maximum objective function value is considered. These records were downloaded by Pacific Earthquake Engineering Research Center (PEER) [25] database.

Table 2. Properties of adjacent structures

Story	Structure 1 [26]			Structure 2 [27]		
	m_i (t)	k_i (kN/m)	c_i (kNs/m)	m_i (t)	k_i (kN/m)	c_i (kNs/m)
10	360	650000	6200	98	34310	442.599
9				107	37430	482.847
8				116	40550	523.095
7				125	43670	563.343
6				134	46790	603.591
5				143	49910	643.839
4				152	53020	683.958
3				161	56140	724.206
2				170	52260	674.154
1				179	62470	805.863

Table 3. The ground motions

Earthquake	Date	Station	Component	PGA (g)	PGV (cm/s)	PGD (cm)
Cape Mendocino	1992	Petrolia	PET090	0.662	89.7	29.55
Kobe	1995	0 KJMA	KJM000	0.821	81.3	17.68
Erzincan	1992	95 Erzincan	ERZ-NS	0.515	83.9	27.35
Northridge	1994	Rinaldi	RRS228	0.838	166.1	28.78
Northridge	1994	24514 Sylmar	SYL360	0.843	129.6	32.68
Loma Prieta	1989	16 LGPC	LGP000	0.563	94.8	41.18

ICCS Camera Ready Version 2021
To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77970-2_9

The optimum results are reported in Table 4 for HS and FPA, respectively. During the optimization, sp (harmony memory considering rate in HS) is taken as 0.5, and the optimization is done for a population number of 20. The ranges of T_d are selected between 0.8 and 1.2 times of the critical period of the uncontrolled structure. Also, the range for ξ_d is 0.01-0.20. The range of m_d is equal to 1%-5% of the total mass of the structures.

Table 4. The optimum results

	FPA	HS
$\mathrm{m_d}$ (t)	180	180
m_d (t)	69.25	69.07
$\mathrm{T_d}$ (s)	0.90	0.92
T_d (s)	1.6175	1.87
$\mathrm{\xi_d}$	0.01	0.02
ξ_d	0.01	0.04
f(X) (m)	1.1219	1.1366

The maximum objective function value for uncontrolled structures is 1.4361 m and it occurs under the Rinaldi record of the 1994 Northridge earthquake. This value reduces to 1.2119 m and 1.1366 m for FPA and HS optimized TMDs, respectively. The optimal design obtained by the FPA is similar to that by HS, but FPA is more effective in reducing the displacement.

4 Conclusions

The optimum result for the reduction of the objective functions shows great differences for both algorithms. As known, the mass of TMD is maximum for the best design of TMD, but it is limited for the axial force capacity of the structure. In that situation, FPA is effective to find TMD with maximum allowed mass, while HS also finds the maximum for the first structure and a near maximum one for the second structure.

In Fig.2, the objective function values for different excitations are given for all stories of the structure. Since the optimization is done for the maximum value, the value of the 10^{th} story is the considered one for the optimization. The best effect of the optimum TMD system is seen for the critical excitation with the most effect on relative displacements of the structure. For the Rinaldi record of the Northridge earthquake, the objective function values reduce by 22% and 21% for FPA and HS, respectively.

ICCS Camera Ready Version 2021
To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77970-2_9

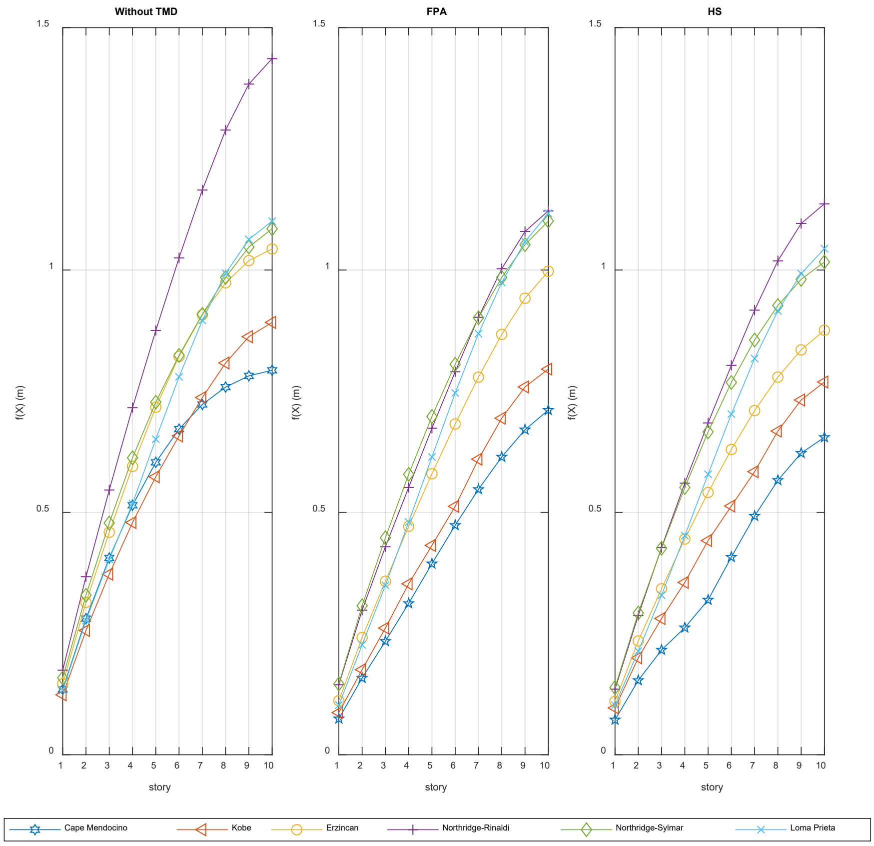

Fig 2. The f(X) values for all excitations

As seen from the findings, FPA is more effective than HS for finding a precise value. It is also seen that TMD application reduces the value of the seismic gap required between the structures.

The performance of TMD is validated for all excitations that are used in this study, but the best performance is seen for the most critical excitation. In that situation, it can be said that TMDs for adjacent structures are most effective on the responses with the maximum effect.

References

1. Jeng, V. and Tzeng, W.L. (2000), "Assessment of seismic pounding hazard for Taipei City", *Eng. Struct.*, 22, 459–471
2. Ni, Y.Q., Ko, J.M. and Ying, Z.G. (2001), "Random Seismic Response Analysis of Adjacent Buildings Coupled with Non-Linear Hysteretic Dampers", *Journal of Sound and Vibration*, 246(3), 403-417.

ICCS Camera Ready Version 2021
To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77970-2_9

3. Anagnostopoulos, S.A. and Karamaneas, C.E. (2008), "Use of collision shear walls to minimize seismic separation and to protect adjacent buildings from collapse due to earthquake-induced pounding", Earthquake Engng Struct. Dyn., 37, 1371–1388.
4. Matsagar, V.A. and Jangid, R.S. (2005), "Viscoelastic damper connected to adjacent structures involving seismic isolation", *Journal of Civil Engineering and Management*, 11(4), 309-322.
5. Polycarpou, P.C., Komodromos, P. and Polycarpou, A.C. (2013), "A nonlinear impact model for simulating the use of rubber shock absorbers for mitigating the effects of structural pounding during earthquakes", Earthquake Engng Struct. Dyn., 42, 81–100.
6. Tubaldi, E., Barbato, M. and Ghazizadeh, S. (2012), "A probabilistic performance-based risk assessment approach for seismic pounding with efficient application to linear systems", *Structural Safety*, **36–37**, 14–22.
7. Bigdeli, K. and Hare, W. (2012), "Tesfamariam S. Configuration optimization of dampers for adjacent buildings under seismic excitations", *Eng Optim*, **44**, 1491-1509.
8. Trombetti, T. and Silvestri, S. (2007), "Novel schemes for inserting seismic dampers in shear-type systems based upon the mass proportional component of the Rayleigh damping matrix", *Journal of Sound and Vibration*, 302, 486-526
9. Nigdeli, S. M., & Bekdas, G. (2014). Optimum tuned mass damper approaches for adjacent structures. *Earthquakes and Structures*, *7*(6), 1071-1091.
10. Bharti, S.D., Dumne, S.M. and Shrimali, M.K. (2010), "Seismic response analysis of adjacent buildings connected with MR dampers", *Eng. Struct.*, 32, 2122-2133.
11. Sheikh, M.N., Xiong, J. and Li, W.H. (2012), "Reduction of seismic pounding effects of base-isolated RC highway bridges using MR damper", *Structural Engineering and Mechanics*, 41(6), 791-803.
12. Cundumi, O. and Suarez, L.E. (2008), "Numerical Investigation of a Variable Damping Semiactive Device for the Mitigation of the Seismic Response of Adjacent Structures", Computer-aided civil and infrastructure engineering, 23, 291-308.
13. Kim, G.C. and Kang, J.W. (2011), "Seismic response control of adjacent building by using hybrid control algorithm of MR", *Procedia Engineering*, 14, 1013-1020.
14. Xu, Y.L. and Zhang, W.S. (2002), "Closed-form solution for seismic response of adjacent buildings with linear quadratic Gaussian controllers", *Earthquake Engng Struct. Dyn.*, 31, 235–259
15. Park, K.-S. and Ok S.-Y. (2012), "Optimal design of actively controlled adjacent structures for balancing the mutually conflicting objectives in design preference aspects", Eng. Struct., 45, 213–222.
16. Guenidi, Z., Abdeddaim, M., Ounis, A., Shrimali, M. K., & Datta, T. K. (2017). Control of adjacent buildings using shared tuned mass damper. Procedia engineering, 199, 1568-1573.
17. Wu, Q. Y., Zhu, H. P., & Chen, X. Y. (2017). Seismic fragility analysis of adjacent inelastic structures connected with viscous fluid dampers. Advances in Structural Engineering, 20(1), 18-33.
18. Basili, M., De Angelis, M., & Pietrosanti, D. (2019). Defective two adjacent single degree of freedom systems linked by spring-dashpot-inerter for vibration control. Engineering Structures, 188, 480-492.
19. Azimi, M., & Yeznabad, A. M. (2020). Swarm-Based Parallel Control of Adjacent Irregular Buildings Considering Soil–Structure Interaction. Journal of Sensor and Actuator Networks, 9(2), 18.
20. Lin, X., Chen, S., & Lin, W. (2020). Modified crow search algorithm–based fuzzy control of adjacent buildings connected by magnetorheological dampers considering soil–structure interaction. Journal of Vibration and Control, 1077546320923438.

ICCS Camera Ready Version 2021
To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77970-2_9

21. Nigdeli, S. M., & Bekdaş, G. (2020, April). Hybrid Harmony Search Algorithm for Optimum Design of Vibration Absorber System for Adjacent Buildings. In International Conference on Harmony Search Algorithm (pp. 73-79). Springer, Singapore.
22. Wang, Q., Qiao, H., De Domenico, D., Zhu, Z., & Tang, Y. (2020). Seismic response control of adjacent high-rise buildings linked by the Tuned Liquid Column Damper-Inerter (TLCDI). Engineering Structures, 223, 111169.
23. Yang, X. S. (2012). Flower pollination algorithm for global optimization. In International conference on unconventional computing and natural computation (pp. 240-249). Springer, Berlin, Heidelberg.
24. Mathworks (2010) MATLAB R2010a. The MathWorks Inc., Natick, MA,USA.
25. Pacific Earthquake Engineering Research Center (PEER). Strong Ground Motion Databases, https://peer.berkeley.edu/peer-strong-ground-motion-databases.
26. Singh, M. P., Matheu, E. E., & Suarez, L. E. (1997). Active and semi-active control of structures under seismic excitation. Earthquake engineering & structural dynamics, 26(2), 193-213.
27. Sadek, F., Mohraz, B., Taylor, A. W., & Chung, R. M. (1997). A method of estimating the parameters of tuned mass dampers for seismic applications. Earthquake Engineering & Structural Dynamics, 26(6), 617-635.

ICCS Camera Ready Version 2021
To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77970-2_9