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SLIDING MODE CONTROL OPTIMIZED BY GENETIC ALGORITHM FOR BUILDING MODEL

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Abstract. *Sliding mode control (SMC) has been used in many mechanical systems and structural system due to its robustness, simplicity and high control performance. However, choosing optimum parameters for systems is still an important research area. This study presents a numerical analysis to decrease the effect of earthquake vibrations on building model having Active Tuned Mass Damper (ATMD). The system is excited by an earthquake and a linear motor is used as the control device. ATMD is installed on top floor of building model. Tuning of Sliding Mode Controller (SMC) with Genetic Algorithm (GA) is designed for a three storey building model with ATMD. SMC parameters have been chosen by GA with a single objective function and a multiple objective function. Then, simulation results of uncontrolled and controlled model are compared. The results show that building model with SMC tuned by GA is effective to decrease the effects of earthquakes.*

1 INTRODUCTION

Many researches have been studied about controlling structural vibration due to potential failure risk or serious damage on buildings. Therefore, vibration control techniques have been improved recently.

The tuned mass damper (TMD), invented in 1909, is a passive control system consisting of mass, springs and viscous dampers. Buildings are protected from hazardous effects of vibrations by using these systems. The optimum parameters of tuned mass dampers (TMD) for different systems are proposed by several researchers; obtained optimum TMD parameters for complex Systems by Warburton and Ayorinde [1-2], gained optimum damper parameters with a frequency locus method by Thompson [3], suggested new approach for TMD by Villaverde [4-6], improved study of Vilaverde by Sadek [7]. Also, semi-active vibration methods are proposed in the literature. Yoshida and Fujio [8] applied a semi-active control method to a base in which the viscous damping coefficient is changed for vibration control. The numerical result indicates that efficiency of semi active TMD is better than conventional TMD, especially under the uncertainty of primary system [9].

Recent research and development activities in the field of vibration control are active vibration control systems emerged around 1970. These systems are active while resisting force exceeds the capacity of a passive-tuned-mass damper [10]. In order to control vibrations more effectively, numerous active control algorithms have been suggested. Guclu and Yazici [11] designed Fuzzy logic and PD controllers for a multi-degree-of freedom structure with active tuned mass damper (ATMD) to suppress earthquake-induced vibrations. Yagiz [12] designed sliding mode control for controlling the vibration of multi-degree of freedom structures with an Active Tuned Mass Damper (ATMD) installed at the top floor to suppress earthquake or wind induced vibration. Essential requirements for sliding mode control are the hitting time reduction and chattering attenuation [13]. Bartolini [14], Bengiamin and Kauffmann [15] suggested inserting an integrator to the system to smooth the chattering but the system response was slow down. To manage the chattering problem, Hwang and Lin [16], Lin and Chen [17] applied the fuzzy set theory. Pourzeynali et. al. [18] was suggested that integration of the GAs and fuzzy logic controller to obtain optimum values of ATMD is highly effective in reduction of seismically excited building.

This study presents a numerical analysis to decrease the effect of earthquake vibrations on building model having Active Tuned Mass Damper (ATMD). To select suitable gain switching and sliding surface parameter is significant for system performance. The searching of these parameters has been done by two different fitness functions with Genetic Algorithm. Sliding Mode Controller (SMC) tuning with Genetic Algorithm (GA) are designed for a three storey building model with ATMD. The simulation results of uncontrolled and controlled model are compared.

2 BUILDING MODEL WITH ATMD

The building model has three degree of freedom (Figure 1). ATMD has been placed on top floor of the building model. m_i, k_i and b_i ($i = 1,2,3$) denotes the mass, stiffness and damping values related to each storey of the building model and m_4, k_4 and b_4 stand for the mass, stiffness and damping values of the ATMD respectively.

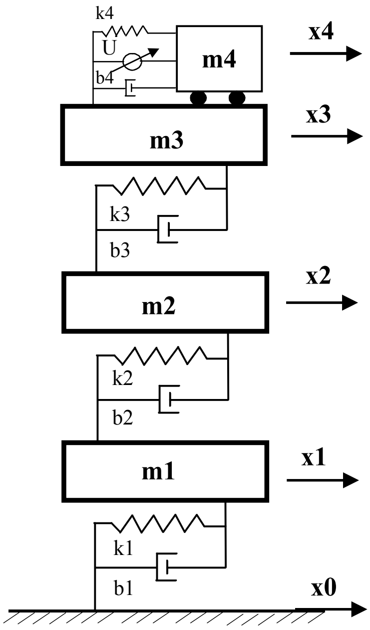

Figure 1: The psychical model of building model.

The mathematical model of the three-storey building model with ATMD has obtained using Lagrange's equations and presented Eq. (1). The system has been excited by El-Centro earthquake.

$$[M]\ddot{x}_i(\mathrm{t})+[B]\dot{x}_i(\mathrm{t})+[K]x_i(\mathrm{t})=P_i(\mathrm{t}) \quad (1)$$

$$x(\mathrm{t})=[x_1 \quad x_2 \quad x_3 \quad x_4]^T \quad (2)$$

Mass, stiffness and damping matrix is shown in Eqs. (3-5).

$$[M]=diag[m_1 \quad m_2 \quad m_3 \quad m_4] \quad (3)$$

$$[B]=\begin{bmatrix} b_1+b_2 & -b_2 & 0 & 0 \\ -b_2 & b_2+b_3 & -b_3 & 0 \\ 0 & -b_3 & b_3+b_4 & -b_4 \\ 0 & 0 & -b_4 & b_4 \end{bmatrix} \quad (4)$$

$$[K]=\begin{bmatrix} k_1+k_2 & -k_2 & 0 & 0 \\ -k_2 & k_2+k_3 & -k_3 & 0 \\ 0 & -k_3 & k_3+k_4 & -k_4 \\ 0 & 0 & -k_4 & k_4 \end{bmatrix} \quad (5)$$

A linear motor is used as the control device. Linear motor force F_u, has been calculated using Eqs. (6) and (7) as shown in Eq. (8).

$$Ri+K_e(\dot{x}_4-\dot{x}_3)=u \quad (6)$$

$$F_u=K_f i \quad (7)$$

$$F_u=\left(K_f / R\right)u-\left(K_e K_f / R\right)(\dot{x}_4-\dot{x}_3) \quad (8)$$

$$E_{ATMD}=F_u(\mathrm{t})\Delta x_4 \quad (9)$$

External loads have consisted of earthquake force and control force shown in Eq. (10).

$$[P] = \begin{bmatrix} -m_1\ddot{x}_0 & -m_2\ddot{x}_0 & -m_3\ddot{x}_0 - F_u & -m_4\ddot{x}_0 + F_u \end{bmatrix}^T \tag{10}$$

3 PARAMETER SELECTION FOR BUILDING MODEL

The mass and stiffness parameters of the building model have been taken from study of Sadek [7]. The damping parameters have been derived from $C = (0.0129)K$ [19] and the parameter of the ATMD has been shown Table 1-2.

Number of Floors	Mass ratio	Tuning Ratio (f)	TMD damping ratio (ξ)	$M_1 = \Phi_1^T [M] \Phi_1$ (10^3 kg)	ω_{01} (Hz)
3	0.100	0.8701	0.3694	271	1.41

Table 1: Ratios for building model (adapted from Sadek [7]).

Floor	Mass (10^3 kg)	Stiffness (kN/m)	Damping Coefficient (kNs/m)
1	100	41000	528.9
2	100	38000	490.2
3	100	36000	464.4
ATMD	27.1	1610.73	154.35

Table 2: Parameters of building model with ATMD (adapted from Sadek [7]).

4 CONTROL STRATEGY

4.1 Sliding Mode Control

Sliding Mode Control is a variable structure control method. Sliding controller design provides a systematic approach to the problem of maintaining stability and consistent performance in the face of modelling imprecisions [20]. Sliding mode control theory has been applied to many nonlinear systems. The main idea is to bring and keep the error on a sliding surface such that the system is insensitive to the disturbances and parameter changes [21-22]. Sliding surface can be chosen as Eq. (10). Δx is error matrix. $[G]$ contains gradient of sliding surface.

$$\sigma = [G][\Delta X] = \underbrace{[G][X_r]}_{A} - [G][X] \tag{11}$$

A Lyapunov function is chosen and must have a value greater than zero, whereas its derivative should be smaller than zero.

$$V(\sigma) = (\sigma^T \sigma)/2 > 0 \quad \dot{V}(\sigma) = \sigma^T \dot{\sigma} \leq 0 \tag{12}$$

According to limit situation can be calculate control input in sliding surface.

$$\dot{\sigma} = \frac{d[A]}{dt} - [G]\{f(x) + [B]u\} = 0 \Rightarrow u_{eq} \tag{13}$$

$$\dot{\sigma} = -[\Gamma](\sigma) \Rightarrow u \tag{14}$$

$$\underbrace{\left[GB\right]^{-1}\left\{\frac{d\left[A\right]}{dt}-\left[G\right]f(x)\right\}}_{u_{eq}}+\left[GB\right]^{-1}\left[\Gamma\right]\left(\sigma\right)=u \tag{15}$$

Suggested that the equivalent control is the average of the total control [23] an averaging filter is used for calculation. The equivalent control is shown in Eq. (16).

$$\hat{u}_{eq}=\frac{1}{\tau s+1}u \tag{16}$$

$$u=\hat{u}_{eq}+\left[GB\right]^{-1}\left[\Gamma\right]\left(\sigma\right) \tag{17}$$

The system must be defined in state space form as $\dot{x}=f(x)+\left[B\right]\underline{u}+\left[C\right]\underline{w}$

$$\begin{gathered}\left[X_1\quad X_2\quad X_3\quad X_4\quad X_5\quad X_6\quad X_7\quad X_8\quad X_9\quad X_{10}\quad X_{11}\quad X_{12}\right]^T=\\ \left[x_1\quad x_2\quad x_3\quad x_4\quad \dot{x}_1\quad \dot{x}_2\quad \dot{x}_3\quad \dot{x}_4\quad x_0\quad \dot{x}_0\quad U\quad \ddot{x}_0\right]^T\end{gathered} \tag{18}$$

$$\begin{bmatrix}\dot{X}_1\\ \dot{X}_2\\ \dot{X}_3\\ \dot{X}_4\\ \dot{X}_5\\ \dot{X}_6\\ \dot{X}_7\\ \dot{X}_8\end{bmatrix}=\begin{bmatrix}X_5\\ X_6\\ X_7\\ X_8\\ \left(\left(-k_1-k_2\right)/m_1\right)X_1+\left(k_2/m_1\right)X_2+\left(\left(-b_1-b_2\right)/m_1\right)X_5+\left(b_2/m_1\right)X_6\\ \left(k_2/m_2\right)X_1+\left(\left(-k_2-k_3\right)/m_2\right)X_2+\left(k_3/m_2\right)X_3+\left(b_2/m_2\right)X_5+\left(\left(-b_2-b_3\right)/m_2\right)X_6+\left(b_3/m_2\right)X_7\\ \left(k_3/m_3\right)X_2+\left(\left(-k_3-k_4\right)/m_3\right)X_3+\left(k_4/m_3\right)X_4+\left(b_3/m_3\right)X_6+\left(\left(-b_3-b_4-\frac{K_eK_f}{R}\right)/m_3\right)X_7+\left(\left(b_4+\frac{K_eK_f}{R}\right)/m_3\right)X_8\\ \left(k_4/m_4\right)X_3+\left(-k_4/m_4\right)X_4+\left(\left(b_4+\frac{K_eK_f}{R}\right)/m_4\right)X_7+\left(\left(-b_4-\frac{K_eK_f}{R}\right)/m_4\right)X_8\end{bmatrix}$$

$$+\begin{bmatrix}0\\0\\0\\0\\0\\0\\-K_f/Rm_3\\K_f/Rm_4\end{bmatrix}\left[u\right]+\begin{bmatrix}0\\0\\0\\0\\ \left(b_1/m_1\right)X_{10}+\left(k_1/m_1\right)X_9-X_{12}\\-X_{12}\\-X_{12}\\-X_{12}\end{bmatrix}\left[w\right] \tag{19}$$

$$\left[G\right]=\left[0\quad 0\quad \alpha\quad 0\quad 0\quad 0\quad 1\quad 0\right] \tag{20}$$

The control law can be shown in Eq. (21).

$$[u]=\hat{u}_{eq}-\frac{Rm_3}{K_f}[\Gamma]\left\{\alpha\underbrace{\left(X_{3r}-X_3\right)}_{e}+\underbrace{\left(X_{7r}-X_7\right)}_{\dot{e}}\right\} \tag{21}$$

4.2 Sliding Mode Control Parameters Tuned by Genetic Algorithm

Genetic Algorithms (GAs) used principles inspired by genetic processes occurring in nature to evolve solutions to problems. GAs usually consist of reproduction, crossover and mutation operators. A fitness function must be devised for each problem to be solved [18]. While the fitness function is minimum, the optimum SMC parameters will be obtained.

The aim of Multi-Objective Optimization with Genetic Algorithm is minimization of multiple fitness function simultaneously. The multi objective genetic algorithm is used to solve multi objective optimization problems by identifying the Pareto front - the set of evenly distributed non dominated optimal solutions [24-25].

The proposed method can efficiently choose the appropriate gain parameters α, Γ for sliding mode controller based on two proposed fitness functions. First fitness function is devised to obtain maximum reduction in the third floor response. The aim of the second fitness function is minimizing the control energy and also minimizing third floor's response quantity. GA is implemented for tuning of the parameters of sliding mode controller. The optimum value of gain parameters α, Γ obtained by GA is used to simulated structural system. The flowchart of the control algorithm is shown as Figure 2.

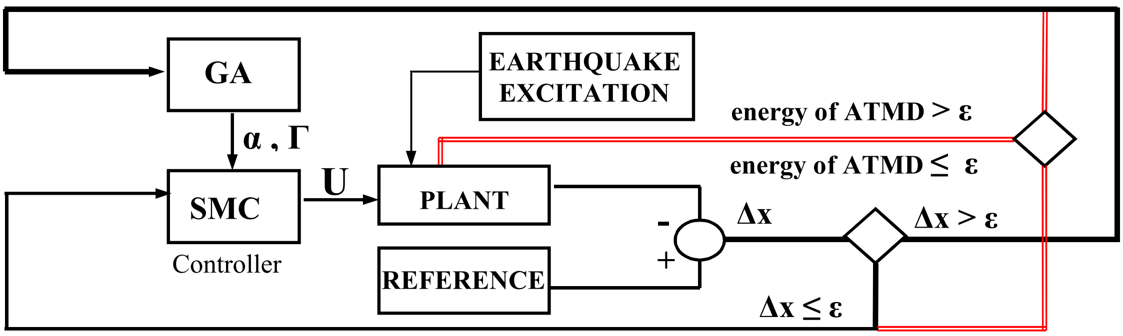

Figure 2: The flowchart of control algorithm.

5 SIMULATION RESULTS

5.1 GA's Fitness Function

The value of minimized third floor's response is scanned by Genetic Algorithm. The fitness function is as below.

$$\phi_1(\alpha, \Gamma) = \sum_{ti}^{tf} e(t) = \sum_{ti}^{tf} \left[x_{3r}(t) - x_3(t) \right] \tag{22}$$

The optimum value of α, Γ is [125 127]. Maximum reduction in the building response has been obtained but the value of the control force may have been considerably high. The result has shown in Table 3. Total energy consumed by ATMD is 3586.75 kJ with the parameters.

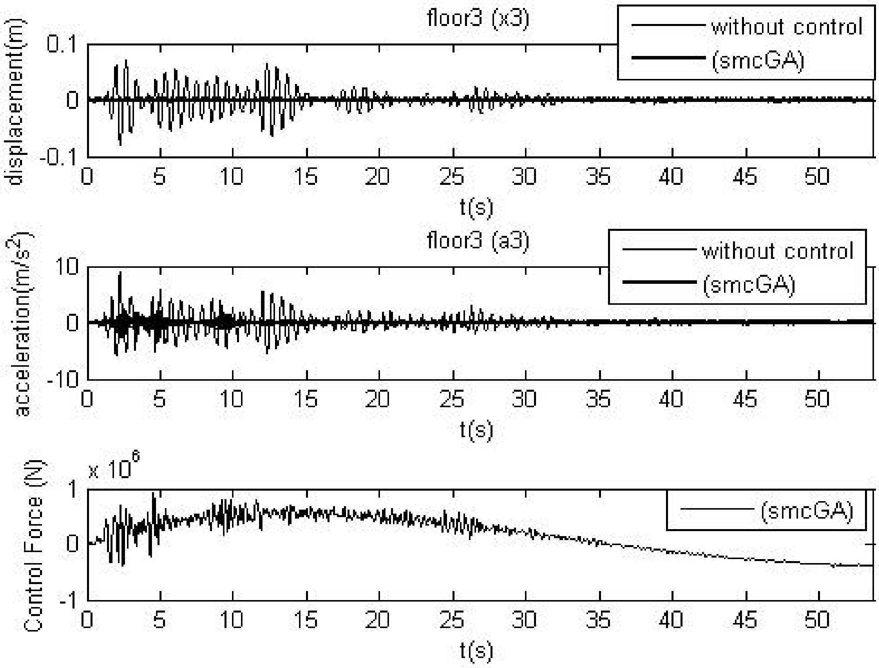

Figure 3: Displacement, acceleration and control force of floor 3.

Floor	Sum of Error Displacement(m)	
	Without Controller	SMCGA
1	10.8338	2.8445
2	20.3912	3.0354
3	26.1084	0.0585

Floor	Peak Values Displacement(m)		Peak Values Acceleration(m/s^2)		RMS Values Displacement(m)		RMS Values Acceleration(m/s^2)	
	Without Controller	SMCGA	Without Controller	SMCGA	Without Controller	SMCGA	Without Controller	SMCGA
1	0.02947	0.01228	4.843	6.643	0.00677	0,00183	0.655	0.667
2	0.05999	0.01317	6.951	7.037	0.01276	0.00195	1.148	0.714
3	0.08012	0.00032	8.899	2.752	0.01634	0.00004	1.461	0.236
ATMD	-	0.47408	-	28.323	-	0.22501	-	3.965

Table 3: Sum Error, Peak and RMS Values of all floors.

5.2 Multi Objective GA's Fitness Functions

Due to the value of the control force is considerably high, trade-off has been made. So control energy is decreased. The multi objective GA's fitness functions are as below.

$$\phi_1(\alpha,\Gamma)=\sum_{ti}^{tf} e(\mathrm{t}) \tag{23}$$

$$\phi_2(\alpha,\Gamma)=E_{ATMD} \tag{24}$$

Multi Objective Genetic Algorithm has been used for minimizing both third floor's displacement and the control energy. The results have been shown in Table 4.

Situation	α	Γ	Error of Floor3 (m)		Energy of ATMD (kJ)	
			RMS Values	Peak Values	RMS Values	Total Values
1	125	127	0.00004	0.00032	2.6622	3586.75
2	19	126	0.00018	0.00126	1.7805	1682.02
3	16	127	0.00019	0.00136	1.7163	1557.23
4	2	127	0.00029	0.00190	1.3142	959.51
5	1	56	0.00063	0.00404	1.2505	896.96
6	16	8	0.00282	0.01682	1.4464	1032.81
7	2	7	0.00337	0.02342	0.7873	531.75
8	19	2	0.00572	0.04455	0.7729	504.93
9	1	1	0.00798	0.05134	0.1711	130.64

Table 4: The values of third floor and the control energy using second fitness function.

Table 4 presents the sum of optimum parameters of sliding mode controller. The best value for the displacement has been obtained with first parameters and the less energy value has been derived with ninth parameters in Table 4. Although the minimum value of the displacement has been got by using first parameter in Table 4, the control force is instable shown as Figure 3.

When the maximum value of displacement of third floor is 0.01m, the first five parameters values have been proved displacement limit. Yet the most appropriate is fifth parameters due to less energy consumption. So 75% of the energy savings have been achieved with these parameters to compare with first parameters in Table 4. System responses with fifth parameters are shown in Figure 4.

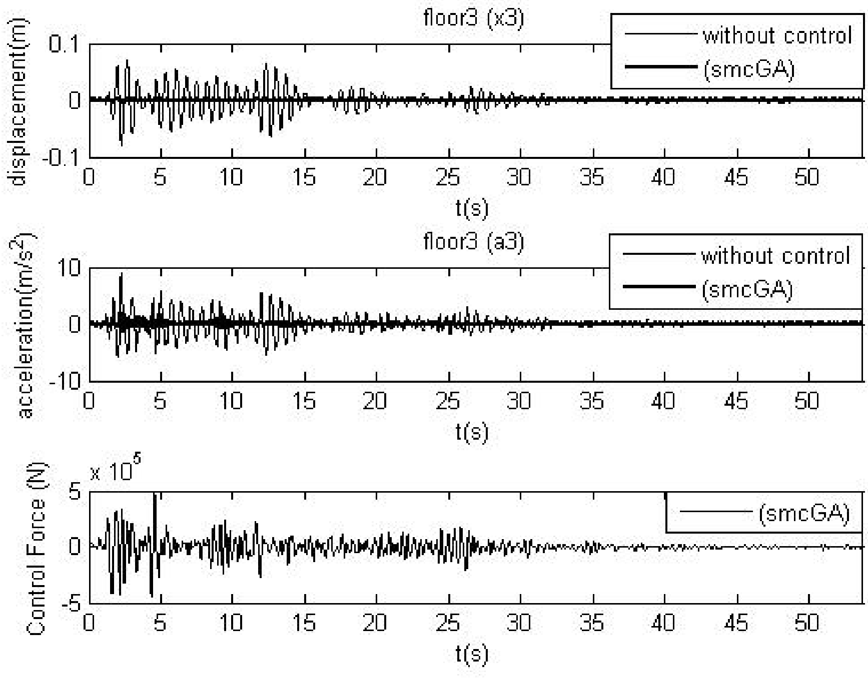

Figure 4: Displacement, acceleration and control force of floor 3 (MOGA).

6 CONCLUSIONS

In this study, Active Tuned Mass Damper (ATMD) with sliding mode controller tuned by Genetic Algorithm has been designed to reduce the vibrations of the three storey building model. The optimum values of sliding mode controller parameters (α, Γ) are obtained by Genetic Algorithm. Thus, the displacement of third floor has been reduced with the optimum values of parameter. Yet, the total energy of the controller has quite high. Therefore, the proposed controller is optimized to create a balance between the consumed energy and performance of controller by using Multi Objective Genetic Algorithms.

When the parameters of sliding mode controller by using Multi Objective Genetic Algorithm have been utilized, the different value of displacement and total energy has been acquired. Due to design limitations of the structure, the parameters caused the minimum energy consumption for control will be determined. The peak displacement value of third floor has been decreased by 95 % to compare system for uncontrolled and controlled with Multi Objective Genetic Algorithm. There is trade-off between the consumed energy and performance thus the energy consumed by controller has decreased by 75 %. Consequently, parameter optimization is useful to obtain optimum results.

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