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GENETIC ALGORITHM INTEGRATED SLIDING MODE CONTROL OF A VEHICLE

HASAN O. OZER [*], ALAATTIN SAYIN [‡], NURAY KORKMAZ [†], NURKAN YAGIZ [†]

[*] Istanbul University, Programme of Air Conditioning and Refrigeration Technology,
Vocational School of Technical Science, 34320, Istanbul, Turkey,
e-mail: omurozer@istanbul.edu.tr

[‡] Istanbul University, Programme of Biomedical Equipment Tech.,
Vocational School of Technical Science, 34320, Istanbul, Turkey,
e-mail: sayina@istanbul.edu.tr

[†] Istanbul University, Department of Mechanical Engineering,
Faculty of Engineering, 34320, Istanbul, Turkey,
e-mail: nkorkmaz@istanbul.edu.tr
e-mail: nurkany@istanbul.edu.tr

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Abstract. The main propose of suspension systems is to isolate car body motion from the road excitations and improve the ride comfort. Hence, to control of suspension system is important both comfort and road holding. The aim of this study is to design Sliding Mode Controller tuned by Genetic Algorithm (GA) for providing smooth vertical motion of car body. Sliding mode control (SMC) has been used in many mechanical and structural systems due to its robustness, simplicity and high control performance. However, tuning optimum controller parameters for systems is still an important research area. The proposed SMC parameters have been tuned by GA with several fitness functions to get better dynamic performance. The vehicle model is excited by random road data. Then, simulation results of uncontrolled and GA integrated sliding mode controllers models are compared. The results show that vehicle model with SMC tuned by GA is effective to decrease the effects of road induced vibrations.

1 INTRODUCTION

Many researchers have been studied controlling vehicle suspension systems to obtain better ride comfort, road holding properties. Therefore, many vibration control techniques and vehicle suspension systems have been improved recently. Passive, semi-active and active suspension systems are currently studied. However, Active suspension systems have more potential to meet high performances requirements [1, 2].

Sharp and Hassan [1] calculated different combinations of spring stiffness and damping coefficient representing the passive suspension system in a quarter car model subject to realistic external disturbances. Williams [3] studied to find the convenient damping ratio for passive suspension systems for a quarter-car model and active suspension systems was designed. Ahmadian and Pare [4] compared to performance of three different semi-active control methods. Yao et al. [5] developed a semi-active control for vehicle suspension system with magnetorheological (MR) damper. In order to control vibrations more effectively, numerous active control algorithms have been suggested [6, 7, 8, 9, 10]. Huisman et al. [6] presented active control strategy for quarter car model. $H\infty$ control was used in active vehicle suspension system by Du and Zhang [7]. Teja and Srinivasa [8] investigated a stochastically PID controller for a linear quarter car model.

Sliding Mode Control (SMC) is a variable structure control method and insensitive to parameter variation and external disturbances [9, 10]. Due to these advantages, SMC is commonly used in robotics [11], vibration control at structures [12, 13, 14, 15], flight control [16], and path control of underwater vehicles [17]. Essential requirements for sliding mode control are the hitting time reduction and chattering attenuation [15]. Yagiz [18] applied the non-chattering sliding mode control to a full vehicle model. To select suitable gain switching and sliding surface parameter is significant for system performance. Thus, sliding mode control was combined with fuzzy logic, neural network and genetic algorithm. Huang and Lin [19] proposed an adaptive fuzzy sliding mode controller for a quarter car test rig. Choi et al. [10] suggested a moving switching surface to reduce the time of the reaching phase. Yagiz et al. [9] researched fuzzy sliding mode control for a half vehicle. Eski and Yildirim [21] used neural network based robust control system for vehicle vibration system. Cheng et al. [10] presented GA-based adaptive fuzzy sliding model controller for a nonlinear system. Javadi-Moghaddama and Bagheri [17] suggested an adaptive neuro-fuzzy sliding-mode-based genetic algorithm control system for a remotely operated vehicle with four degrees of freedom for tracking control. Ozer et al. [15] used sliding mode control based genetic algorithm to decrease vibration at the structure with ATMD.

The aim of this study is to improve the ride comfort of the vehicle. Thus, Sliding Mode Controller tuned by Genetic Algorithm (GA) has been designed for providing smooth vertical motion of a car body. Firstly, a four degree of freedom nonlinear half car model is described in detail. Then, the proposed SMC parameters have been tuned by GA with several fitness functions to get better dynamic performance. The vehicle model is excited by random road data and is simulated with the proposed control system. Finally, the results of proposed controlled and uncontrolled systems are given and discussed.

2 VEHICLE MODEL

In this study, four degree of freedom vehicle model is used as shown in Figure 1. In this model, y is body bounce; θ is the pitch motion of the vehicle body; y_1 is the displacement of the front wheels and y_2 is the displacement of the front wheels.

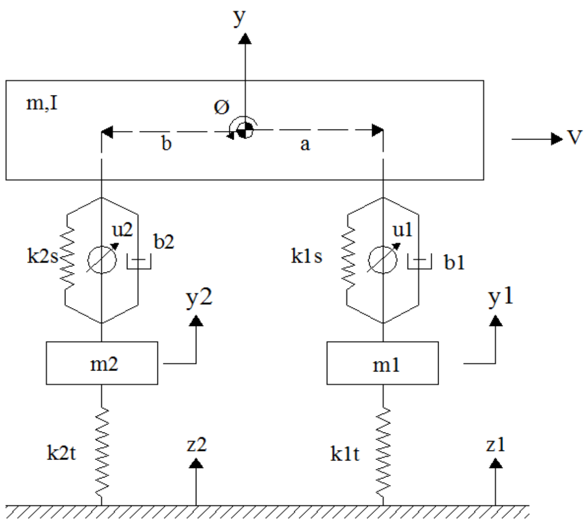

Figure 1: The psychical model of half-vehicle model

Total kinetic, potential and dissipative energy of the model are;

$$K = \frac{1}{2}m\dot{y}^2 + \frac{1}{2}m_1\dot{y}_1{}^2 + \frac{1}{2}m_2\dot{y}_2{}^2 + \frac{1}{2}I\dot{\theta}^2 + \frac{1}{2}mV^2 \tag{1}$$

$$P = \frac{1}{2}k_1t(y_1 - z_1)^2 + \frac{1}{2}k_2t(y_2 - z_2)^2 + \frac{1}{2}k_1s(y + a\sin\theta - y_1)^2 + \frac{1}{2}k_2s(y - b\sin\theta - y_2)^2 \tag{2}$$

$$D = \frac{1}{2}b_1(\dot{y} + a\cos\theta.\dot{\theta} - \dot{y}_1)^2 + \frac{1}{2}b_2\left(\dot{y} - b\cos\theta.\dot{\theta} - \dot{y}_2\right)^2 \tag{3}$$

The equation of motion is obtained by using Lagrange's equations and can therefore be expressed as,

$$\begin{aligned} &m\ddot{y} + b_1(\dot{y} + a\cos\theta.\dot{\theta} - \dot{y}_1) + b_2(\dot{y} - b\cos\theta.\dot{\theta} - \dot{y}_2) + k_1s(y + a\sin\theta - y_1) \\ &+k_2s(y - b\sin\theta - y_2) = U(y) = u_1 + u_2 \end{aligned} \tag{4}$$

$$\begin{aligned} &I\ddot{\theta} + b_1a\cos\theta.(\dot{y} + a\cos\theta.\dot{\theta} - \dot{y}_1) - b_2b\cos\theta(\dot{y} - b\cos\theta.\dot{\theta} - \dot{y}_2) \\ &+k_1s(y + a\sin\theta - y_1).a\cos\theta - k_2s(y - b\sin\theta - y_2)b\cos\theta = U(\theta) = u_1a - u_2b \end{aligned} \tag{5}$$

$$m_1\ddot{y}_1 - b_1(\dot{y} + a\cos\theta.\dot{\theta} - \dot{y}_1) + k_1t(y_1 - z_1) - k_1s(y + a\sin\theta - y_1) = U(1) = -u_1 \tag{6}$$

$$m_2\ddot{y}_2 - b_2(\dot{y} - b\cos\theta.\dot{\theta} - \dot{y}_2) + k_2t(y_2 - z_2) - k_2s(y - b\sin\theta - y_2) = U(2) = -u_2 \tag{7}$$

The equation of motion can be written in matrix form as,

$$\left[M\right]\ddot{x}_i(t) + \left[B\right]\dot{x}_i(t) + \left[K\right]x_i(t) = P_i(t) \tag{8}$$

Mass, stiffness, damping matrix, external loads and control forces are shown in Eqs. (9-11).

$$x(\mathrm{t}) = [x_1 \quad x_2 \quad x_3 \quad x_4]^T \qquad \left[M\right] = diag[m \quad I \quad m_1 \quad m_2] \tag{9}$$

$$\left[B\right] = \begin{bmatrix} b_1 + b_2 & b_1 a - b_2 b & -b_1 & -b_2 \\ b_1 a - b_2 b & b_1 a^2 + b_2 b^2 & -b_1 a & b_2 b \\ -b_1 & -b_1 a & b_1 & 0 \\ -b_2 & b_2 b & 0 & b_2 \end{bmatrix} \left[K\right] = \begin{bmatrix} k_1 s + k_2 s & ak_1 s - bk_2 s & -k_1 s & -k_2 s \\ ak_1 s - bk_2 s & a^2 k_1 s + b^2 k_2 s & -ak_1 s & bk_2 s \\ -k_1 s & -ak_1 s & k_1 s + k_1 t & 0 \\ -k_2 s & bk_2 s & 0 & k_2 s + k_2 t \end{bmatrix} \tag{10}$$

$$\left[P\right] = \left[U(\mathrm{y}) \quad U(\theta) \quad U(1) + \mathrm{k}_1 t\left(z_1\right) \quad U(2) + \mathrm{k}_2 t\left(z_2\right)\right]^T \tag{11}$$

3 CONTROL STRATEGY

3.1 Sliding Mode Control

Sliding Mode Control is a variable structure control method and design provides a systematic approach to the problem of maintaining stability and consistent performance in the face of modeling imprecision [12, 15]. Sliding mode control theory has been many applications for nonlinear systems. The basics of the control are to bring and keep the error on a sliding surface such that the system is insensitive to the disturbances and parameter changes [13-14]. Sliding surface can be chosen as Eq. (12). Δx is error matrix. $\left[G\right]$ contains gradient of sliding surface.

$$\sigma = \left[G\right]\left[\Delta X\right] = \underbrace{\left[G\right]\left[X_r\right]}_{A} - \left[G\right]\left[X\right] \tag{12}$$

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

$$V\left(\sigma\right) = \left(\sigma^T \sigma\right)/2 > 0 \quad \dot{V}\left(\sigma\right) = \sigma^T \dot{\sigma} \le 0 \tag{13}$$

Due to limit situation, the control input in sliding surface can be calculated as below;

$$\dot{\sigma} = \frac{d\left[A\right]}{dt} - \left[G\right]\left\{f(x) + \left[B\right]u\right\} = 0 \Rightarrow u_{eq} \tag{14}$$

$$\dot{\sigma} = -\left[\Gamma\right]\left(\sigma\right) \Rightarrow u \tag{15}$$

$$\underbrace{\left[GB\right]^{-1}\left\{\frac{d\left[A\right]}{dt} - \left[G\right]f(x)\right\}}_{u_{eq}} + \left[GB\right]^{-1}\left[\Gamma\right]\left(\sigma\right) = u \tag{16}$$

It is suggested that the equivalent control is the average of the total control [23] and the averaging filter is used to calculate the control value. The equivalent control is shown in Eq. (17).

$$\hat{u}_{eq} = \frac{1}{\tau s + 1} u \tag{17}$$

$$u = \hat{u}_{eq} + \left[GB\right]^{-1}\left[\Gamma\right]\left(\sigma\right) \tag{18}$$

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

$$\begin{bmatrix} X_1 & X_2 & X_3 & X_4 & X_5 & X_6 & X_7 & X_8 \end{bmatrix}^T = \begin{bmatrix} y & \theta & y_1 & y_2 & \dot{y} & \dot{\theta} & \dot{y}_1 & \dot{y}_2 \end{bmatrix}^T \tag{19}$$

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \\ \dot{X}_4 \\ \dot{X}_5 \\ \dot{X}_6 \\ \dot{X}_7 \\ \dot{X}_8 \end{bmatrix} = \begin{bmatrix} X_5 \\ X_6 \\ X_7 \\ X_8 \\ -\frac{b_1}{m}(X_5 + a\cos(X_2).X_6 - X_7) - \frac{b_2}{m}(X_5 - b\cos(X_2).X_6 - X_8) - \frac{k_1 s}{m}(X_1 + a\sin(X_2) - X_3) - \frac{k_2 s}{m}(X_1 - b\sin(X_2) - X_4) \\ -\frac{b_1 a}{I}\cos(X_2)(X_5 + a\cos(X_2)X_6 - X_7) + \frac{b_2 b}{I}\cos(X_2)(X_5 - b\cos(X_2)X_6 - X_8)\ldots \\ \ldots - \frac{k_1 s}{I}(X_1 + a\sin(X_2) - X_3).a\cos(X_2) + \frac{k_2 s}{I}(X_1 - b\sin(X_2) - X_4)b\cos(X_2) \\ +\frac{b_1}{m_1}(X_5 + a\cos(X_2)X_6 - X_7) - \frac{k_1 t}{m_1}(X_3) + \frac{k_1 s}{m_1}(X_1 + a\sin(X_2) - X_3) \\ +\frac{b_2}{m_2}(X_5 - \mathrm{b}\cos(X_2)X_6 - X_8) - \frac{k_2 t}{m_2}(X_4) + \frac{k_2 s}{m_2}(X_1 - \mathrm{b}\sin(X_2) - X_4) \end{bmatrix}$$

$$+ \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1/m & 0 & 0 & 0 \\ 0 & 1/I & 0 & 0 \\ 0 & 0 & 1/m_1 & 0 \\ 0 & 0 & 0 & 1/m_2 \end{bmatrix} \begin{bmatrix} U(\mathrm{y}) \\ U(\theta) \\ U(1) \\ U(2) \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \mathrm{k}_1 t & 0 \\ 0 & \mathrm{k}_2 t \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \tag{20}$$

$$[G] = \begin{bmatrix} \alpha_1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & \alpha_2 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & \alpha_3 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & \alpha_4 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad [\Gamma] = \begin{bmatrix} \Gamma_1 & 0 & 0 & 0 \\ 0 & \Gamma_2 & 0 & 0 \\ 0 & 0 & \Gamma_3 & 0 \\ 0 & 0 & 0 & \Gamma_4 \end{bmatrix} \tag{21}$$

$$[u] = \hat{u}_{eq} + \left\{ \begin{bmatrix} m\Gamma_1 & 0 & 0 & 0 \\ 0 & I\Gamma_2 & 0 & 0 \\ 0 & 0 & m_1\Gamma_3 & 0 \\ 0 & 0 & 0 & m_2\Gamma_4 \end{bmatrix} \begin{bmatrix} \alpha_1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & \alpha_2 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & \alpha_3 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & \alpha_4 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_{1r} - X_1 \\ X_{2r} - X_2 \\ X_{3r} - X_3 \\ X_{4r} - X_4 \\ X_{5r} - X_5 \\ X_{6r} - X_6 \\ X_{7r} - X_7 \\ X_{8r} - X_8 \end{bmatrix} \right\} \tag{22}$$

The control laws can be shown in Eq. (23).

$$\mathrm{U(y)} = \hat{U}(\mathrm{y})_{eq} + m\Gamma_1 \left\{ \alpha_1 \left(X_{1r} - X_1 \right) + \left(X_{5r} - X_5 \right) \right\},\ \mathrm{U}(\theta) = \hat{U}(\theta)_{eq} + I\Gamma_2 \left\{ \alpha_2 \left(X_{2r} - X_2 \right) + \left(X_{6r} - X_6 \right) \right\} \tag{23}$$

3.2 Sliding Mode Control Parameters Tuned by Genetic Algorithm

Genetic Algorithms (GAs) has been depended on Darwinian principle in biological mutation and reproduction, survival-of the-fittest. This principle is used to evolve solutions to problems. A genetic algorithm consists of three main operators; reproduction, crossover and mutation operators. A fitness function must be suggested for each problem [24]. Minimum or maximum solution of cost function is the solution of the problem.

The idea of Multi-Objective Optimization with Genetic Algorithm minimizes 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 [25-26].

The proposed method can efficiently choose the appropriate gain parameters α,Γ for sliding mode controller based on two proposed fitness functions. The aim of the fitness function is devised to obtain frequency response reduction for the body and pitch motion.

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 simulate the vehicle model. The flowchart of the control algorithm is shown as Figure 2.

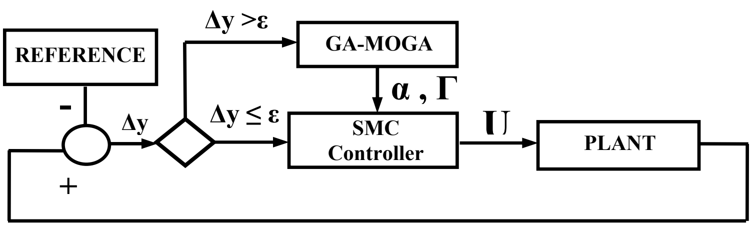

Figure 2: The flowchart of control algorithm

4 SIMULATION RESULTS

4.1 GA's Fitness Function

Two different cost functions are chosen to get minimum value of the total frequency response First cost function minimizes the total frequency response of the body bounce and second one minimizes of the total frequency response of pitch motion. The general form of the cost function is shown Eq.(24).

$$\phi_1\left(\alpha,\Gamma\right) = \min \sum_{fi}^{ff} H(j\omega) \tag{24}$$

The Genetic algorithm has been run with two individual cost function. Optimum results have been shown as Figure 3. It is clear from this figure that first resonance peak due to a vehicle body which is around 1 Hz, is eliminated by SMC GA. Yet, second resonance peak is superior. The human body is more sensitive to vertical vibration between 4 Hz and 8 Hz [H. Gao et. al 2006]. Therefore, the elimination of first resonance has improved ride comfort remarkably. The magnitude of the first resonance for pitch motion is also reduced.

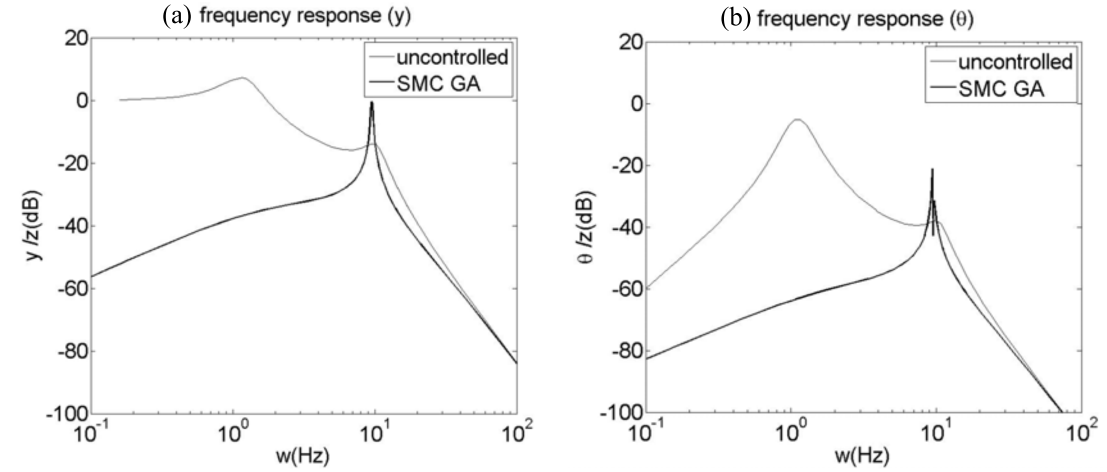

Figure 3: The frequency response of vehicle model with different values: (a) body bounce (y) ($[\alpha\ \Gamma] = [12\ \ 186]$), (b) pitch motion (θ)$[\alpha\ \Gamma] = [32\ \ 160]$

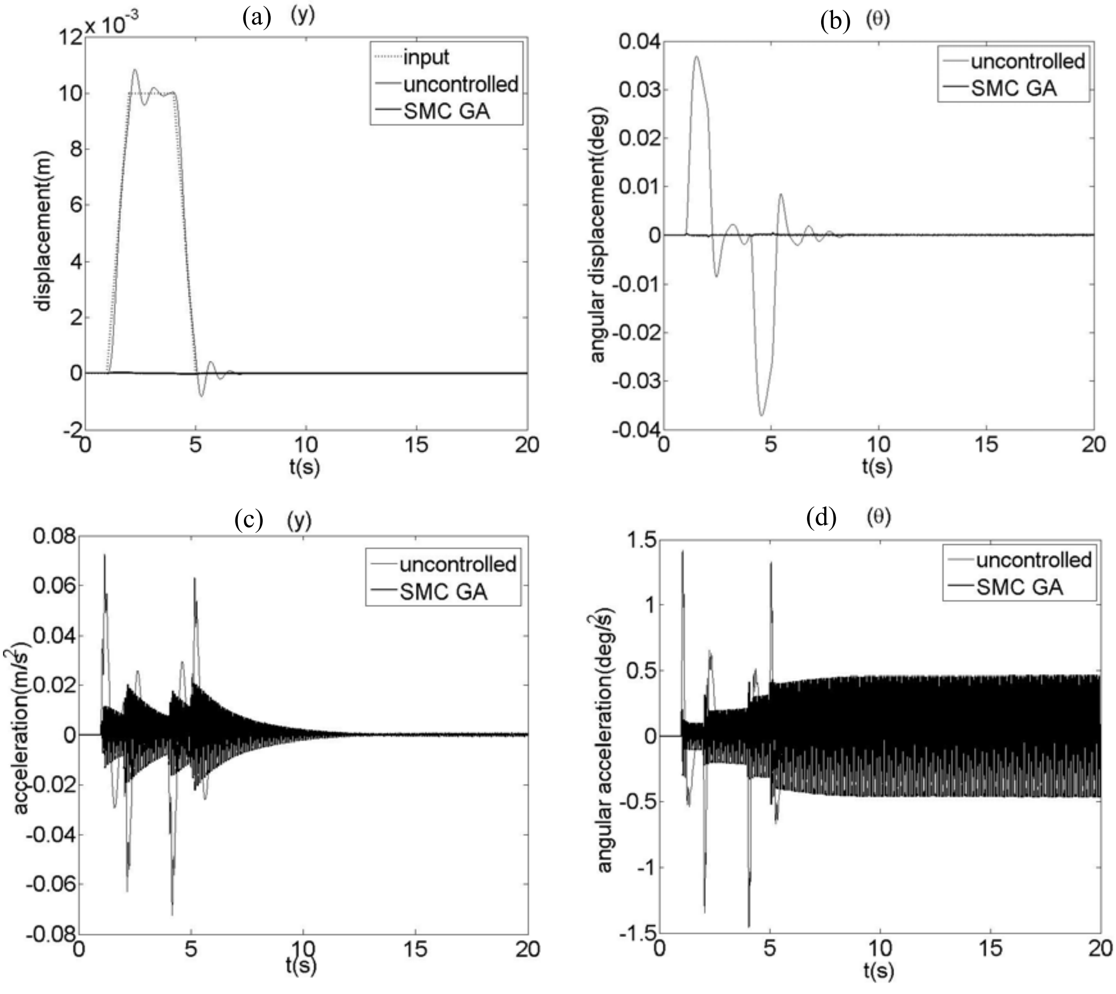

Figure 4: The uncontrolled and SMC MOGA controlled vehicle responses: (a) body bounce (y), (b) pitch motion (θ), (c) vertical acceleration of the vehicle body , (d) angular acceleration of the vehicle body

Although the magnitudes of body bounce and pitch motion is decreased significantly with respect to uncontrolled model, vertical and angular acceleration is worse that the uncontrolled one as shown Figure 4. Therefore, the responses of acceleration and displacement must be checked before chosen suitable parameters for the system. Optimum values are researched with multi objective genetic algorithm by using SCM GA values as upper boundary for $\left[\alpha\ \Gamma\right]$ values.

4.2 Multi Objective GA's Fitness Functions

The optimum values minimized both the frequency response of θ and y were researched by Multi Objective genetic algorithm to obtain the controller coefficients $\left[\alpha_1\ \Gamma_1\right]$ and $\left[\alpha_2\ \Gamma_2\right]$. The cost functions were separated two regions. They are 0-9 Hz and 9-10 Hz regions. Figure 3 shows that there is resonance between 9-10 Hz regions. Hence, the individual cost functions were suggested to reduce the resonance amplitude. The objective function is shown below;

$$\phi_1\left(\alpha_1,\Gamma_1\right) = \min \sum_{0Hz}^{9Hz} H(j\omega)\,,\quad \phi_2\left(\alpha_1,\Gamma_1\right) = \min \sum_{9Hz}^{10Hz} H(j\omega) \tag{25}$$

$$\phi_3\left(\alpha_2,\Gamma_2\right) = \min \sum_{0Hz}^{9Hz} H(j\omega)\,,\quad \phi_4\left(\alpha_2,\Gamma_2\right) = \min \sum_{9Hz}^{10Hz} H(j\omega) \tag{26}$$

Different values of the optimum control coefficients $\left[\alpha,\Gamma\right]$ were obtained by multi objective genetic algorithm shown Table 1. Number of iterations is 129. The values in the shaded areas were selected samples for time and frequency response.

Table 1: Several parameters for SMC.

	0-9 Hz (y)	9-10 Hz (y)	0-9 Hz (theta)	9-10 Hz (theta)	α_1	Γ_1	α_2	Γ_2
1	6,765	1,989	25,265	0,053	6,063	123,7	1,9	1,1
2	3,856	2,117	0,312	10,550	11,829	174,7	29,2	129,0
3	222,317	1,003	47,709	0,062	1,708	1,0	26,1	1,0
4	181,430	1,008	69,091	0,062	1,585	2,2	26,1	1,0
5	3,978	2,440	0,311	17,358	10,680	174,7	29,2	129,0
6	3,837	2,596	0,751	0,090	12,000	174,7	1,9	129,6
7	233,732	1,003	14,708	0,062	1,000	1,0	2,0	1,0
8	76,475	1,048	16,471	0,061	1,000	10,6	26,1	1,0
9	3,978	2,456	0,311	18,003	10,683	174,7	29,2	129,0
10	3,839	2,610	0,294	0,357	12,000	174,7	32,0	129,6
11	5,766	1,743	0,306	11,363	11,829	123,7	29,2	129,0
12	45,747	1,057	0,201	0,186	9,613	11,3	32,0	158,8
13	43,581	1,076	0,279	2,723	12,000	11,3	29,2	129,6
14	5,766	1,748	0,306	11,433	11,829	123,7	29,2	129,0
15	177,917	1,008	62,300	0,062	1,708	2,2	26,1	1,0
16	222,523	1,003	47,326	0,062	1,703	1,0	26,1	1,0
17	6,188	1,867	25,418	0,054	1,707	174,7	1,9	1,0
18	209,590	1,005	117,613	0,062	1,586	1,6	26,1	1,0

19	20,189	1,207	0,281	2,674	12,000	31,3	29,2	129,6
20	119,932	1,007	0,727	0,113	12,000	2,2	2,0	129,6
21	158,439	0,810	0,325	10,634	11,814	1,0	29,2	129,0

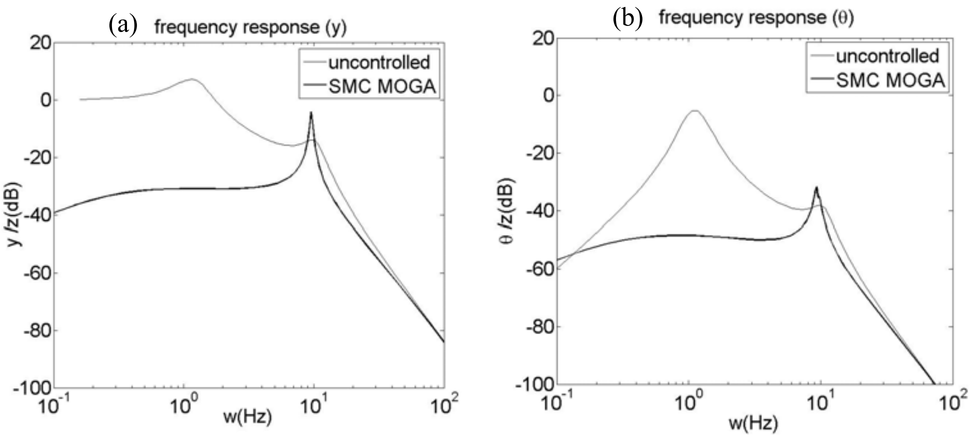

Figure 5: Frequency responses of the vehicle model: (a) body bounce(y) ($[\alpha\ \Gamma]=[1.707\ \ 174.7]$), (b) pitch motion(θ) ($[\alpha\ \Gamma]=[1.9\ \ 129.6]$)

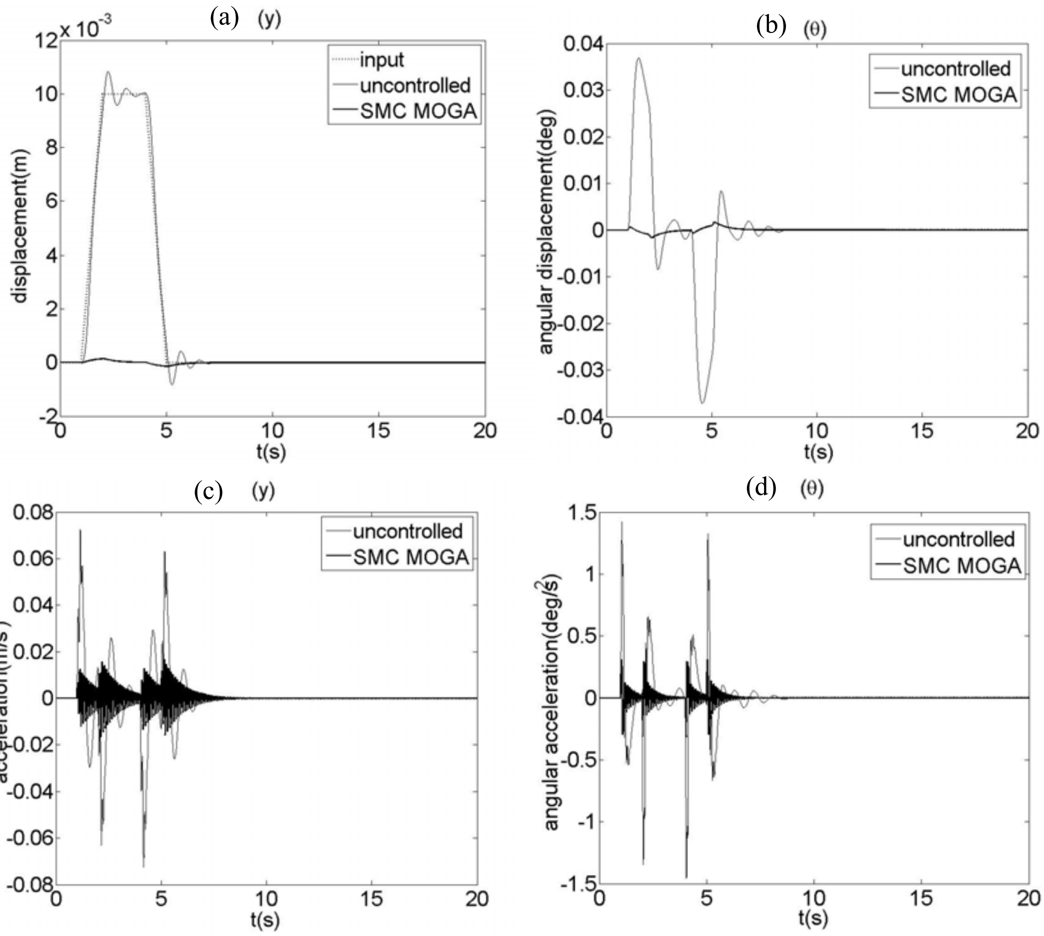

Figure 6: The uncontrolled and SMC MOGA controlled vehicle responses: (a) body bounces(y), (b) pitch motion (θ), (c) vertical acceleration of the vehicle body, (d) angular acceleration of the vehicle body

At the end of Multi Objective Genetic Algorithm process, Optimum controller parameters $[\alpha\, \Gamma]$ were attained. Though these values increase total error of frequency responses, we have significant progress in acceleration responses.

5 CONCLUSIONS

In this study, the optimum values of sliding mode controller parameters $[\alpha\, \Gamma]$ are obtained for the half vehicle model by Genetic Algorithm. The cost function is designed to reduce frequency responses. The proposed sliding mode controller improves ride comfort with controlling body bounce and pitch motion.

Although genetic algorithm obtains best values for frequency responses, the acceleration responses increase significantly. The controller coefficients both body bounce and pitch have been processed simultaneously with the multi-objective genetic algorithm There is trade-off between frequency response and acceleration. Selected different parameters $[\alpha\, \Gamma]$ at table are used to simulate frequency and time responses. The results show that the frequency responses increase significantly and accelerations of the vehicle are quite improved.

Consequently, parameter optimization is useful to obtain optimum results. The parameters of SMC are constant during the simulation. We suggest that using time-invariant coefficients for SMC may be advantage. Therefore, we plan to propose SMC with time-invariant coefficients.

REFERENCES

[1] Sharp, R.S. and Hassan S. A., An Evaluation of passive automotive suspension systems with variable stiffness and damping parameters, *Vehicle System Dynamics* (1986) **15**: 335-350.

[2] Gao, H., Lam J., Wang C., Multi-objective control of vehicle active suspension systems via load-dependent controllers, *Journal of Sound and Vibration* (2006) **290.3:**654-675.

[3] Williams, R. A., Automotive active suspensions Part 1: Basic principles, *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* (1997) **211. 6** :415–426

[4] Ahmadian, M. and Pare, C. A., A quarter-car experimental analysis of alternative semiactive control methods, *Journal of Intelligent Material Systems and Structures* (2000) **11.8**: 604–612.

[5] Yao, G.Z., Yap, F.F., Chen, G., Li, W.H., Yeo, S.H., MR damper and its application for semi-active control of vehicle suspension system, *Mechatronics* (2002) **12.7**: 963-973.

[6] Huisman, R. G. M., Veldpaus, F. E., Voets, H. J. M., and Kok, J. J., An optimal continuous time control strategy for active suspensions with preview, *Vehicle System Dynamics* (1993) **22.1:** 43–55.

[7] Du, H., Zhang, N., H∞ control of active vehicle suspensions with actuator time detay, *Journal of Sound and Vibration* (2007) **301**:236-252.

[8] Teja, S. R. and Srinivasa, Y. G., Investigations on the stochastically optimized PID controller for a linear quarter-car road vehicle, *Vehicle System Dynamics* (1996) **26.2**:103-116.

[9] Yagiz, N., Hacioglu, Y., and Taskin, Y., Fuzzy Sliding-Mode Control of Active Suspensions, *IEEE Transactions On Industrial Electronics* (2008) **55.11**:3883-3890.
[10] Chen, P.C., Chen, C.W., Chiang, W.L., GA-based modified adaptive fuzzy sliding mode controller for nonlinear systems, *Expert Systems with Applications* (2009) **36.3**: 5872-5879.
[11] Ertugrul, M., Kaynak, O., and Sabanovic, A., A comparison of various VSS techniques on the control of automated guided vehicles, *Industrial Electronics ISIE'95 Proceedings of the IEEE International Symposium* (1995) **2**:837-842
[12] Guclu, R., Yazici, H., Vibration control of a structure with ATMD against earthquake using fuzzy logic controllers, *Journal of Sound and Vibration* (2008) **318**:36-49.
[13] Yagiz, N., Sliding Mode Control of a Multi-Degree-of-Freedom Structural System with Active Tuned Mass Damper, *Tr.J. of Engineering and Environmental Science* (2001) **25**:651-657
[14] Wang, A.P., Lee, C.D., Fuzzy sliding mode control for a building structure based on genetic algorithms, *Earthquake Engineering and Structural Dynamics* (2002) **31**:881–895.
[15] Ozer, H. O., Sayin, A., Korkmaz, N., Yagiz, N., Sliding Mode Control Optimized By Genetic Algorithm for Building Model, *11th International Conference on Vibration Problems ICOVP 2013,*(2013) #**218**:1-10
[16] Jafarov, E. M. and Tasaltin, R., Robust sliding mode control for the uncertain MIMO aircraft model F-18, *Aerospace and Electronic Systems IEEE Transactions on* (2000) **36.4**: 1127-1141.
[17] Moghaddam, J. J., Bagheri, A. , An adaptive neuro-fuzzy sliding mode based genetic algorithm control system for under water remotely operated vehicle, *Expert Systems with Applications* (2010), **37.1**: 647-660.
[18] Yagiz, N., Comparison and evaluation of different control strategies on a full vehicle model with passenger seat using sliding modes, *International Journal Of Vehicle Design*, (2004) **34.2**: 168-182.
[19] Huang, S. J. and Lin, W. C., Adaptive fuzzy controller with sliding surface for vehicle suspension control, *Fuzzy Systems, IEEE Transactions on* (2003) **11.4**: 550-559.
[20] Choi, S. B., Cheong, C. C., and Park, D.W., Moving switching surfaces for robust control of second-order variable structure systems, *International Journal of Control* (1993) **58.1**: 229-245.
[21] Eski, I., Yildirim, S., Vibration control of vehicle active suspension system using a new robust neural network control system, *Simulation Modelling Practice and Theory* (2009) **17.5:** 778-793.
[22] Wong, C.C., Chang, S.Y., Parameter Selection in the Sliding Mode Control Design Using Genetic Algorithms, *Tamkang Journal of Science and Engineering* (1998) **1**: 115-122.
[23] Bartolini, G., Chattering phenomena in discontinuous control systems, *International Journal of Systems Science* (1989) **20**: 2471-2481.
[24] J,i H.R., Moon, Y.J., Kim, C.H., Lee, I.W., Structural Vibration Control Using Semiactive Tuned Mass Damper, *The Eighteenth KKCNN Symposium on Civil Engineering-KAIST6* (2005) 18-20.
[25] Bengiamin, N.N., Kauffmann, B., Variable structure position control, *Control Systems Magazine, IEEE* (1984) **4.3:** 3-8.

[26] G.C. Hwang, S.C. Lin, A stability approach to fuzzy control design for nonlinear systems, *Fuzzy sets and Systems* (1992) **48.3:** 279-287.
[27] Ogata, K., *Modern Control Engineering*, Prentice Hall, 1990.
[28] Slotine, J.J., Li, W., *Applied Nonlinear Control*, Prentice Hall, 1991.
[29] Utkin, V.I., *Sliding modes in control optimization*, Springer, 1992.