

Sliding Mode Control Tuned by Multi Objective Genetic Algorithm for a Half Vehicle

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Abstract

The suspension systems is to isolate car body motion from the road excitations and improve the ride comfort. Therefore, controlling of a suspension system is essential for both comfort and road holding. In this study, Sliding Mode Controller tuned by Multi Objective Genetic Algorithm (MOGA) is designed to provide smooth vertical motion of car body. Sliding mode control (SMC) is robust and easy to use. However, tuning optimum controller parameters for systems is still an issue. The proposed SMC parameters have been tuned by MOGA with several fitness functions to get better dynamic performance. The vehicle model is excited by bump input. Then, simulation results of uncontrolled and MOGA integrated Sliding Mode Controllers models are compared. As a result of this study, the vehicle model with SMC tuned by MOGA is effective to decrease the effects of road induced vibrations.

Keywords: Sliding Mode Controller, Multi Objective Genetic Algorithm, Vehicle Model, Simulation of Vehicle Vibrations.

1. Introduction

Controlling of vehicle suspension systems is one of the most important research area. Therefore, many vibration control techniques have been improved nowadays. There are three main suspension systems. These are passive, semi-active and active suspension systems. However, Active suspension systems have more potential to meet high performances requirements (Sharp and Hassan 1986, Gao, Lam and Wang, 2006).

Sliding Mode Control (SMC) is a variable structure control method and insensitive to parameter variation and external disturbances (Yagiz et al., 2008, Chen et al., 2009). Due to these advantages, SMC is commonly used in robotics (Ertugrul, Kaynak and Sabanovic, 1995), vibration control at structures (Guclu and Yazici, 2008, Yagiz, 2001), flight control (Jafarov, and Tasaltin, 2000), and path control of underwater vehicles (Moghaddam and Bagheri, 2010). Essential requirements for sliding mode control are the hitting time reduction and chattering attenuation (Utkin, 1992). Yagiz (2004) 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 (2003) proposed an adaptive fuzzy sliding mode controller for a quarter car test rig. Choi et al. (1993) suggested a moving switching surface to reduce the time of the reaching phase. Yagiz et al. (2008) researched fuzzy sliding mode control for a half vehicle. Eski and Yildirim (2009) used neural network based robust control system for vehicle vibration system. Chen et al. (2009) presented GA-based adaptive fuzzy sliding model controller for a nonlinear system. Moghaddama and Bagheri (2010) 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. (2013) used sliding mode control based genetic algorithm to decrease vibration at the structure with ATMD.

Sharp and Hassan (1986) 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 (1997) 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 (2000) compared to performance of three different semi-active control methods. Yao et al. (2002) 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 (Huisman et al., 1993, Du and Zang, 2007). Huisman et al. (1993) presented active control strategy for quarter car model. H∞ control was used in active vehicle suspension system by Du and Zhang (2007). Teja and Srinivasa (1996) investigated a stochastically PID controller for a linear quarter car model.

The aim of this study is to improve the ride comfort of the vehicle. Therefore, Sliding Mode Controller tuned by Multi-Objective Genetic Algorithm (MOGA) 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 MOGA with four fitness functions to get better dynamic performance. The vehicle model is excited by bump input 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; $\mathbf{y_1}$ is the displacement of the front wheels and $\mathbf{y_2}$ is the displacement of the front wheels.

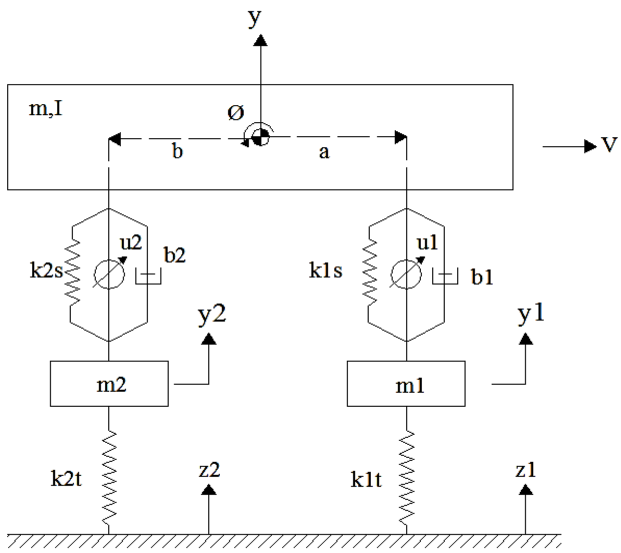

Figure 1. The psychical model of half-vehicle model.

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

$$m\ddot{y} + b_1(\dot{y} + a\cos\theta.\dot{\theta} - \dot{y}_1) + b_2(\dot{y} - b\cos\theta.\dot{\theta} - \dot{y}_2) + k_1 s(y + a\sin\theta - y_1)$$
$$+k_2 s(y - b\sin\theta - y_2) = U(\mathrm{y}) = u_1 + u_2 \quad (1)$$

$$I\ddot{\theta}+b_1 a\cos\theta.(\dot{y}+a\cos\theta.\dot{\theta}-\dot{y}_1)-b_2 b\cos\theta(\dot{y}-b\cos\theta.\dot{\theta}-\dot{y}_2)+k_1 s(y+a\sin\theta-y_1).a\cos\theta$$
$$-k_2 s(y-b\sin\theta-y_2)b\cos\theta=U(\theta)=u_1 a-u_2 b \quad (2)$$

$$m_1\ddot{y}_1-b_1(\dot{y}+a\cos\theta.\dot{\theta}-\dot{y}_1)+k_1 t(y_1-z_1)-k_1 s(y+a\sin\theta-y_1)=U(1)=-u_1 \quad (3)$$

$$m_2\ddot{y}_2-b_2(\dot{y}-b\cos\theta.\dot{\theta}-\dot{y}_2)+k_2 t(y_2-z_2)-k_2 s(y-b\sin\theta-y_2)=U(2)=-u_2 \quad (4)$$

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

$$[M]\ddot{x}_i(\mathrm{t})+[B]\dot{x}_i(\mathrm{t})+[K]x_i(\mathrm{t})=P_i(\mathrm{t}) \quad (5)$$

Mass, stiffness, damping matrix, external loads and control forces are shown in Eqs. (7-10).

$$x(\mathrm{t})=[x_1 \quad x_2 \quad x_3 \quad x_4]^T \quad (6)$$

$$[M]=diag[m \quad I \quad m_1 \quad m_2] \quad (7)$$

$$[B]=\begin{bmatrix} b_1+b_2 & b_1 a-b_2 b & -b_1 & -b_2 \\ b_1 a-b_2 b & b_1 a^2+b_2 b^2 & -b_1 a & b_2 b \\ -b_1 & -b_1 a & b_1 & 0 \\ -b_2 & b_2 b & 0 & b_2 \end{bmatrix} \quad (8)$$

$$[K]=\begin{bmatrix} k_1 s+k_2 s & ak_1 s-bk_2 s & -k_1 s & -k_2 s \\ ak_1 s-bk_2 s & a^2 k_1 s+b^2 k_2 s & -ak_1 s & bk_2 s \\ -k_1 s & -ak_1 s & k_1 s+k_1 t & 0 \\ -k_2 s & bk_2 s & 0 & k_2 s+k_2 t \end{bmatrix} \quad (9)$$

$$[P]=\left[U(\mathrm{y}) \quad U(\theta) \quad U(1)+\mathrm{k}_1 t(z_1) \quad U(2)+\mathrm{k}_2 t(z_2)\right]^T \quad (10)$$

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 (Guclu and Yazici, 2008, Yagiz, 2001, Wang and Lee, 2002, Ozer et al., 2013). 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 (Yagiz, 2001, Wang and Lee, 2002). Sliding surface can be chosen as Eq. (11). Δx is error matrix. $[G]$ contains gradient of sliding surface.

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

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

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

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

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

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

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

It is suggested that the equivalent control is the average of the total control (Ertugrul et al., 1995) and the averaging filter is used to calculate the control value. The equivalent control is shown in Eq. (16).

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

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

The system must be defined in state space form as:

$$\dot{x}=f(x)+[B]\underline{u}+[C]\underline{w} \tag{18}$$

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

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

$$+\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1/m & 0 & 0 & 0 \\ 0 & 1/I & 0 & 0 \\ 0 & 0 & 1/m_1 & 0 \\ 0 & 0 & 0 & 1/m_2 \end{bmatrix}\begin{bmatrix} U(y) \\ U(\theta) \\ U(1) \\ U(2) \end{bmatrix}+\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ k_1 t & 0 \\ 0 & k_2 t \end{bmatrix}\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \tag{20}$$

$$[G]=\begin{bmatrix} \alpha_1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & \alpha_2 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & \alpha_3 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & \alpha_4 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{21}$$

$$[\Gamma]=\begin{bmatrix} \Gamma_1 & 0 & 0 & 0 \\ 0 & \Gamma_2 & 0 & 0 \\ 0 & 0 & \Gamma_3 & 0 \\ 0 & 0 & 0 & \Gamma_4 \end{bmatrix} \tag{22}$$

$$[u]=\hat{u}_{eq}+\left\{\begin{bmatrix} m\Gamma_1 & 0 & 0 & 0 \\ 0 & I\Gamma_2 & 0 & 0 \\ 0 & 0 & m_1\Gamma_3 & 0 \\ 0 & 0 & 0 & m_2\Gamma_4 \end{bmatrix}\begin{bmatrix} \alpha_1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & \alpha_2 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & \alpha_3 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & \alpha_4 & 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} X_{1r}-X_1 \\ X_{2r}-X_2 \\ X_{3r}-X_3 \\ X_{4r}-X_4 \\ X_{5r}-X_5 \\ X_{6r}-X_6 \\ X_{7r}-X_7 \\ X_{8r}-X_8 \end{bmatrix}\right\} \tag{23}$$

The control laws can be shown in Eq. (24-25).

$$\mathrm{U(y)}=\hat{U}(\mathrm{y})_{eq}+m\Gamma_1\left\{\alpha_1\left(X_{1r}-X_1\right)+\left(X_{5r}-X_5\right)\right\} \tag{24}$$

$$\mathrm{U}(\theta)=\hat{U}(\theta)_{eq}+I\Gamma_2\left\{\alpha_2\left(X_{2r}-X_2\right)+\left(X_{6r}-X_6\right)\right\} \tag{25}$$

3.2 Sliding Mode Control Parameters Tuned by Multi Objective 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 (Ji et al., 2005). Minimum or maximum solution of cost function is the solution of the problem.

The idea of Multi-Objective Optimization with Genetic Algorithm (MOGA) 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 (Bengiamin and Kauffmann, 1984, Hwang and Lin, 1992).

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.
MOGA is implemented for tuning of the parameters of sliding mode controller. The optimum value of gain parameters [α, Γ] obtained by MOGA is used to simulate the vehicle model. The flowchart of the control algorithm is shown as Figure 2.

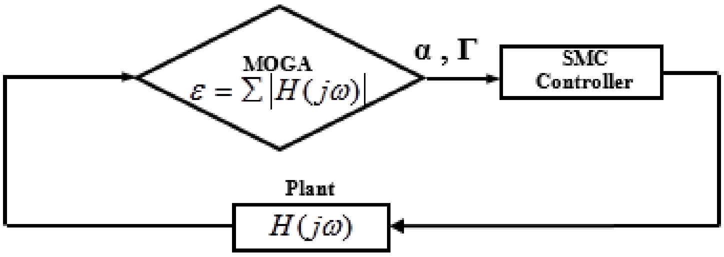

Figure 2. The flowchart of control algorithm.

4. Simulation Results

4.1 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 **[α_1, Γ_1]** and **[α_2, Γ_2]**. The system's resonance frequencies occur at 1 Hz and between 9 and 10 Hz as shown in Figure 3. The cost functions were separated two regions. They are 0-9 Hz and 9-10 Hz regions. Hence, the individual cost functions were suggested to reduce the resonance amplitude. The objective functions are shown below;

$$\phi_1(\alpha_1,\Gamma_1) = \min \sum_{0Hz}^{9Hz} H(j\omega) \quad , \quad \phi_2(\alpha_1,\Gamma_1) = \min \sum_{9Hz}^{10Hz} H(j\omega) \qquad (26)$$

$$\phi_3(\alpha_2,\Gamma_2) = \min \sum_{0Hz}^{9Hz} H(j\omega) \; , \quad \phi_4(\alpha_2,\Gamma_2) = \min \sum_{9Hz}^{10Hz} H(j\omega) \qquad (27)$$

Different values of the optimum control coefficients [α, Γ] were obtained by multi objective genetic algorithm shown Table 1. Number of iterations is 129. The shaded rows indicate the best value to get better results.

Table 1. Several parameters for SMC

	0-9 Hz (y)	**9-10 Hz (y)**	**0-9 Hz (θ)**	**9-10 Hz (θ)**	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

	0-9 Hz (y)	9-10 Hz (y)	0-9 Hz (θ)	9-10 Hz (θ)	α_1	Γ_1	α_2	Γ_2
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

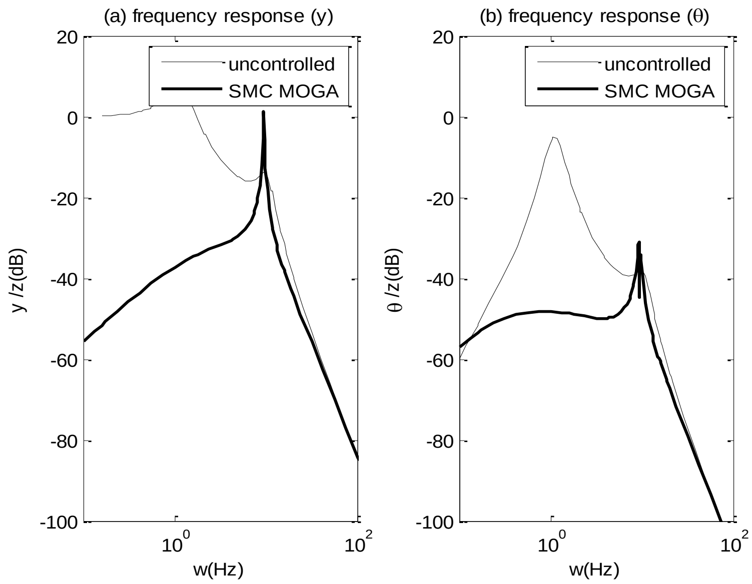

Figure 3. Frequency responses of the vehicle model for the minimum value for body bounce (y) at 0-9 Hz: (a) body bounce(y) ($[\alpha\ \Gamma]=[12\ \ 174.7]$), (b) pitch motion (θ) ($[\alpha\ \Gamma]=[1.9\ \ 129.6]$)

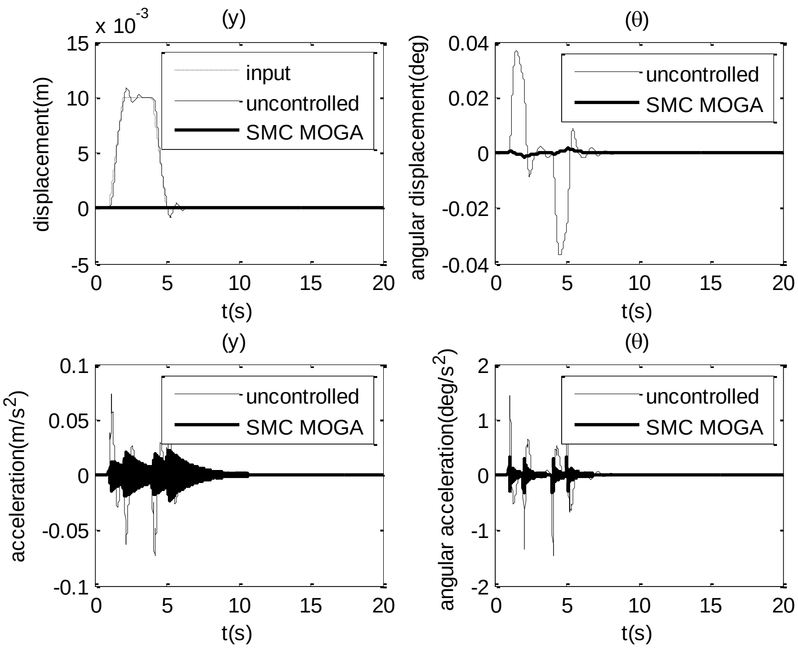

Figure 4. The uncontrolled and SMC MOGA controlled vehicle responses: (a) body bounces(y), (b) pitch motion (θ), (c) vertical acceleration of the vehicle body, (d) angular acceleration of the vehicle body.

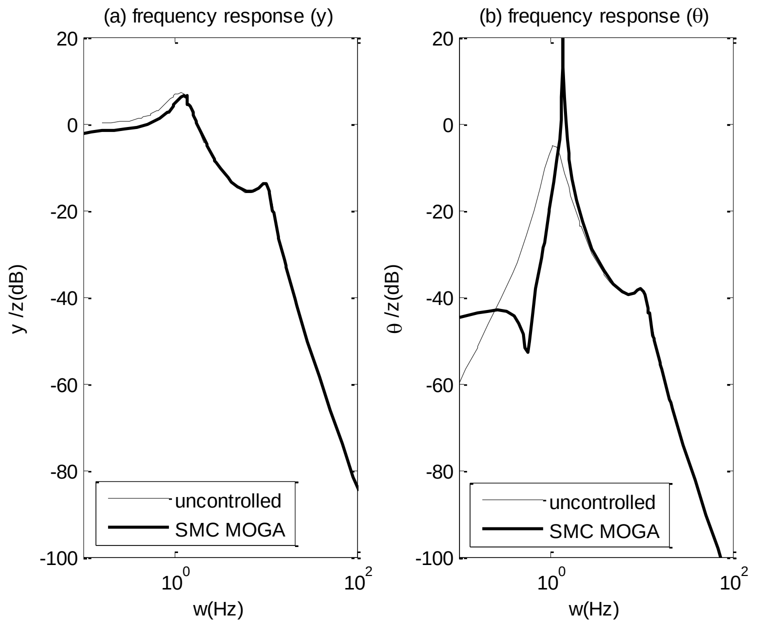

Figure 5. Frequency responses of the vehicle model for the minimum value for body bounce (y) at 9-10Hz: (a) body bounce(y) ($[\alpha\ \Gamma]=[1.708\ \ 1]$),(b) pitch motion(θ) ($[\alpha\ \Gamma]=[26.1\ \ 1]$)

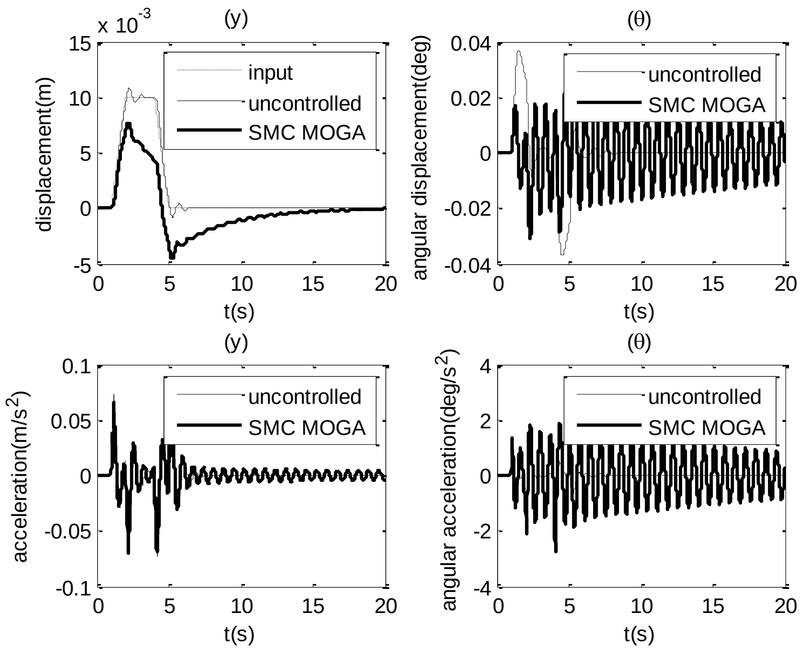

Figure 6. The uncontrolled and SMC MOGA controlled vehicle responses: (a) body bounces(y), (b) pitch motion (θ), (c) vertical acceleration of the vehicle body, (d) angular acceleration of the vehicle body.

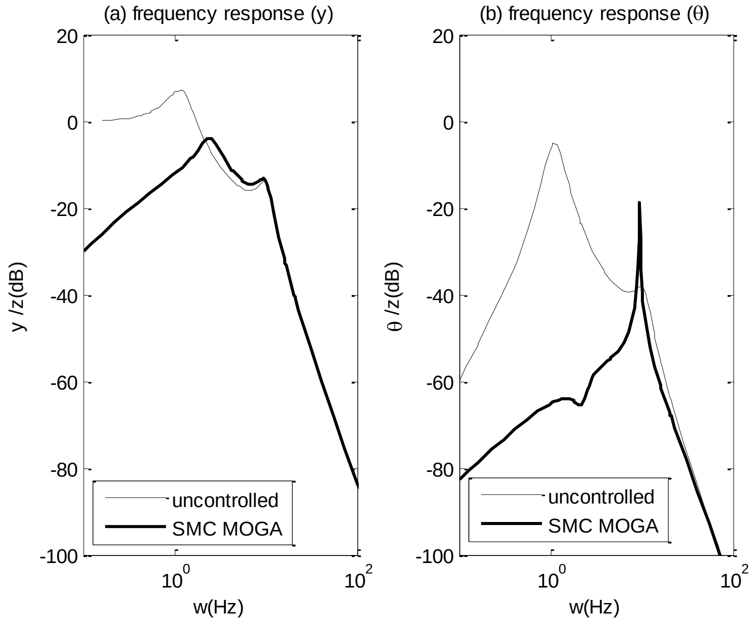

Figure 7. Frequency responses of the vehicle model for the minimum value for pitch motion (θ) at 0-9 Hz: (a) body bounce(y) ($[\alpha\ \Gamma]=[9.613\ \ 11.3]$),(b) pitch motion(θ) ($[\alpha\ \Gamma]=[32\ \ 158.8]$)

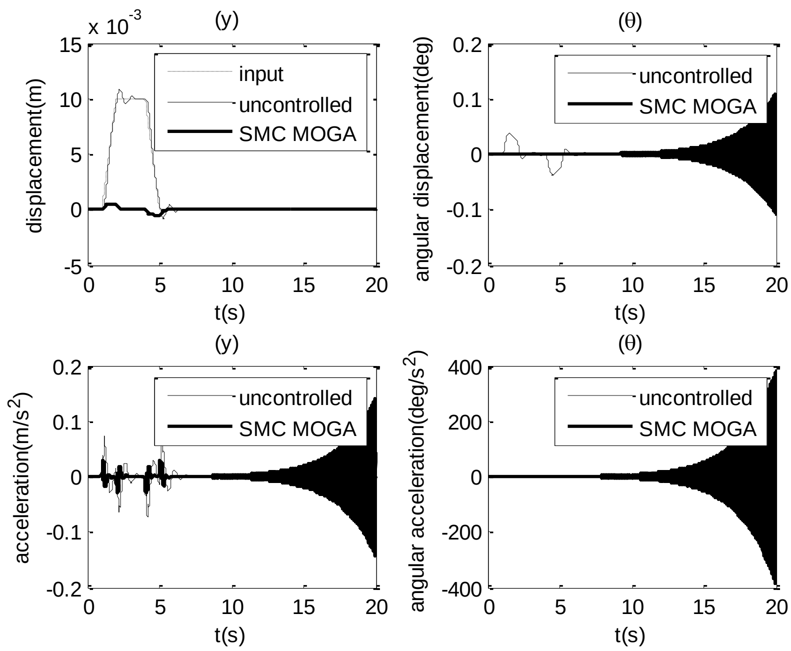

Figure 8. The uncontrolled and SMC MOGA controlled vehicle responses: (a) body bounces(y), (b) pitch motion (θ), (c) vertical acceleration of the vehicle body, (d) angular acceleration of the vehicle body

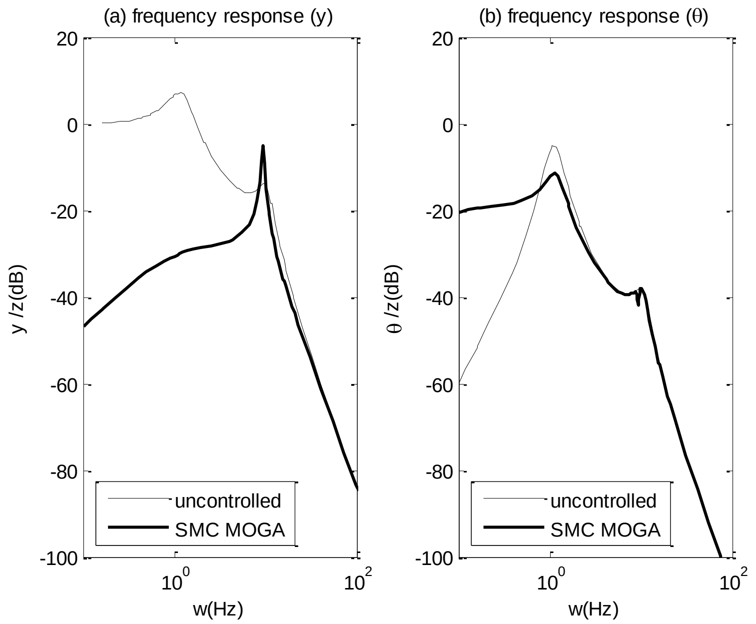

Figure 9. Frequency responses of the vehicle model for the minimum value for pitch motion (θ) at 9-10 Hz: (a) body bounce(y) ($[\alpha\ \Gamma]=[6.063\ \ 123.7]$), (b) pitch motion(θ) ($[\alpha\ \Gamma]=[1.9\ \ 1.1]$)

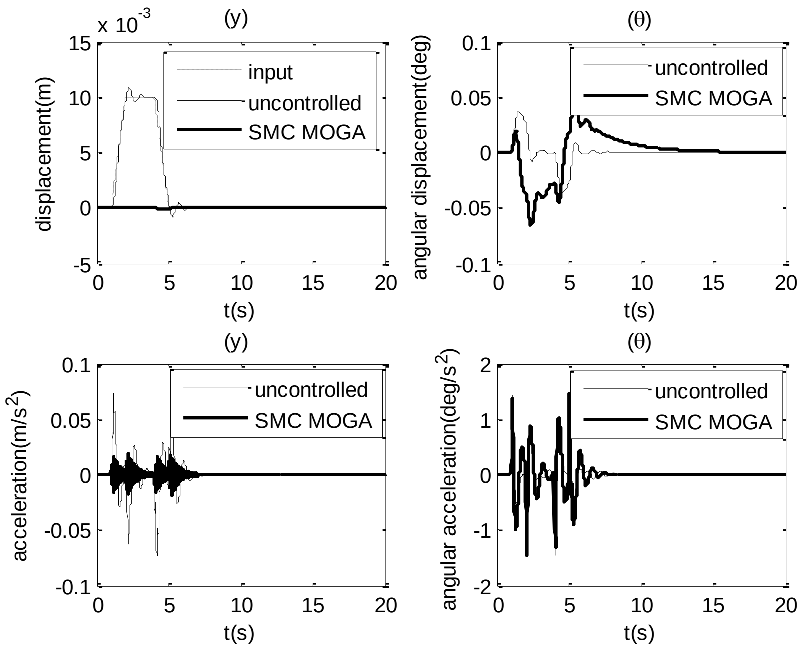

Figure 10. The uncontrolled and SMC MOGA controlled vehicle responses: (a) body bounces(y), (b) pitch motion (θ), (c) vertical acceleration of the vehicle body, (d) angular acceleration of the vehicle body

To getting optimum value for both frequency and acceleration responses with the same parameters is not possible as shown in Figure 3, 5, 7, 9. Therefore, optimization of the system responses leads to a trade-off between system parameter and $[\alpha_1\ \Gamma_1]=[1.707\ \ 174.7], [\alpha_2\ \Gamma_2]=[1.9\ \ 129.6]$. $[\alpha_1\ \Gamma_1][\alpha_2\ \Gamma_2]$ are selected to increase effectiveness under given circumstances, the results are shown in Figure 11.
At the end of Multi Objective Genetic Algorithm process, Optimum controller parameters [α, Γ] were attained. Though these values increase total error of frequency responses, we have significant progress in acceleration responses.

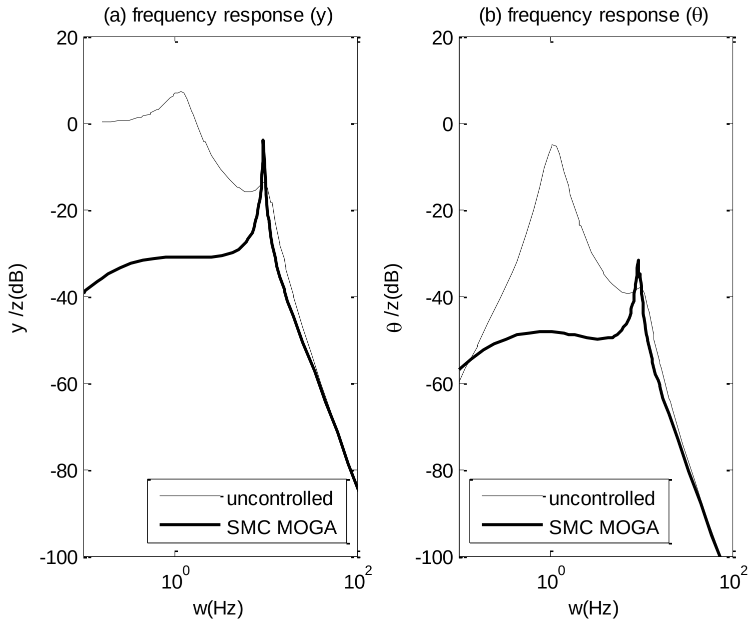

Figure 11. Frequency responses of the vehicle model: (a) body bounce(y) ($[\alpha\ \Gamma]=[1.707\ \ 174.7]$), (b) pitch motion(θ) ($[\alpha\ \Gamma]=[1.9\ \ 129.6]$)

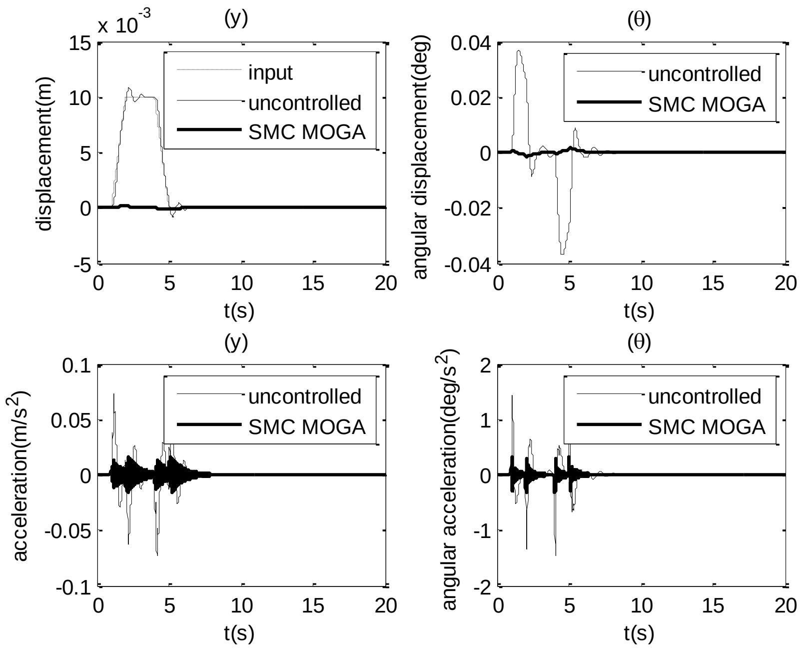

Figure 12. The uncontrolled and SMC MOGA controlled vehicle responses: (a) body bounces(y), (b) pitch motion (θ), (c) vertical acceleration of the vehicle body, (d) angular acceleration of the vehicle body

5. Conclusions

In this study, the optimum values of sliding mode controller parameters [α, Γ] are obtained for the half vehicle model by Multi Objective 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.

The human body is more sensitive to vertical vibration between 4 Hz and 8 Hz (Gao et. al 2006). Therefore, the elimination of first resonance has improved ride comfort remarkably. 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 [α,Γ] 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.

The optimization of the system responses leads to a trade-off between system parameters which are selected to increase effectiveness under given circumstances.

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.

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