Modeling and Analysis of Passive Suspension System Using Half Car Model Based on Hybrid Shock Absorber Model

Vijay Barethiye, G. Pohit, and A. Mitra

Abstract The vehicle suspension system has been a focus of attention to researchers over a long period of time as it improves vehicle stability, handling properties and rode comfort to the passengers. This paper presents modelling and comparative analysis for the passive suspension using linear model (constant damping coefficient) and hybrid shock absorber model. A shock absorber is the vital element of the suspension system and typically characterized by the force-velocity curve which is hysteresis and nonlinear in behaviour. Most of researchers used linear constant damping coefficient to analyze the vehicle performance characteristics. In this work a nonlinear hybrid shock absorber model from established literature is used to analyze the vehicle performances. To developed the hybrid shock absorber model, author used experimental shock absorber damping forces to devise two different models, namely, piecewise linear model and hysteresis model. The hybrid shock absorber model is incorporated into half car suspension system to investigate the influence of damping forces on the response characteristics of a vehicle. The simulated results generated by using hybrid model are compared with linear model and also with the existing published results. The modeling and simulation is carried out by using Simulink for bump road perturbation. The simulation results show that the performance characteristics of vehicle suspension using hybrid shock absorber model improves the road comfort of the passengers. Results corresponding to body displacement, body acceleration and pitch of the vehicle are furnished. It can be concluded that the linear damper model is inadequate to capture the vehicle performance accurately due to the absence of hysteresis force. Hence, to understand and study the performance of the vehicle the hybrid shock absorber model is essential.

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1 Introduction

The vehicle suspension framework is significantly design and developed for segregating vehicle body from road roughness to minimize the vertical acceleration transmitted to the passenger, providing better ride comfort [1–3]. Traditional suspension system consisting of springs and dampers is referred to as passive suspension. The automotive industries use the passive suspension system to control the dynamic performances of a vehicle such as vertical acceleration, pitch and roll. Passive suspension system is found in controlling the dynamics of vertical motion of a vehicle. Even though it does not apply energy to the system, but it controls the relative motion of the body to the wheel by using different types of damping or energy dissipating elements. A shock absorber is an integral part of suspension system. The main function of shock absorber is to control the transient behavior of the sprung and unsprung masses of the vehicle. It performs this task by dissipating energy from the system and hence the reducing the vertical oscillations of the vehicle arising from the unevenness of the road surface. So, it is evident that comfort and road handling performances of a vehicle are mainly determined by the damping characteristics of the shock absorber/damper, which is usually provided a characteristics curve in terms of force-velocity behavior. It should be mentioned here that it is also the least understood and most complex part of the suspension system because of its non-linear and complex behavior. In fact, the damping force of the dampers behaves with unsymmetrical nonlinear hysteresis loop [2]. Hence a good representation of the shock absorber behavior and its analysis is important in vehicle dynamic studies and hence dynamic simulation and analysis of suspension systems is still an interesting research topic in the area of automotive engineering.

Extensive research has been carried out on the analysis of suspension system using simpler shock absorber model such as linear and piecewise bilinear models. Duym et al. [4] highlighted that, worked in the past to simulate vehicle behavior, showed a poor relationship with measured values due to the use of linear damping coefficient. The linear and bilinear models are inadequate to capture the behavior of the shock absorber and hence the characteristics of a vehicle [5–8]. Shock absorber can be model on the basis of physical modeling based on the internal structure or design phenomenon and nonparametric modeling, which can define the relationship by mathematical equations between the force-velocity characteristics of the absorber. Therefore, it is quite tricky to model the shock absorber characteristics which predict the accuracy in the vehicle performances obtained by using nonlinear hysteresis properties. Hence it is important to use the shock absorber model that is capable to determine the vehicle performances accurately.

From literature, several models have been proposed to describe the performance of hydraulic shock absorber and its behavior to study vehicle dynamics. The experimental investigation, laboratory testing and modeling of shock absorber have been carried out by some of the researchers [5–12]. Barethiye et al. [5] carried out laboratory experiment on a car damper utilizing INSTRON to developed hybrid shock absorber model using force-velocity characteristics of the shock absorber. The authors used experimental data to devise two different models, namely, piecewise linear model and hysteresis model, to capture the nonlinear and hysteresis damping properties of the absorber.

It is standard practice to incorporate the shock absorber (may be linear or nonlinear) model into simple quarter car suspension system to study the dynamics of the vehicle. Most of the authors [12–16] used linear or constant damping coefficient to study the dynamics of vehicle using passive and active suspension system for quarter car, half car and full car model. Similarly the capability of shock absorber model should also be investigated for half car simulation with the effect of the nonlinear and hysteresis characteristics of shock absorber on vehicle performance as primary concern. The vertical behavior of vehicle can be observed by using quarter car analysis whereas in addition to vertical behavior the pitch can be analyzed using half car model. The half car model analysis of passive suspension system has been carried out by following researchers with linear and nonlinear damping properties of hydraulic shock absorber.

Demir et al. [17] modeled nonlinear half-vehicle analytically. Then nonlinear parameter for a half car which included quadratic tire stiffness, cubic suspension stiffness, and Coulomb friction were derived based on fundamental physics. Gao et al. [18] investigated the dynamic response of half-car model subjected to random road perturbation. Darsivan [19] presented a half car model simulation and analysis using bilinear model and power law model subjected to step and double pothole road profile. Author used power law damper model to represent the nonlinearity of the damper, located at the front and at the rear axle of the car model.

In this paper a hybrid shock absorber model is incorporated into half car suspension system to investigate the influence of damping forces considering nonlinear and hysteresis properties on the response characteristics of a vehicle. The simulation and analysis for 4-degree of freedom half car modeling with linear constant damping coefficient and hybrid shock absorber model, have been carried out subjected to bump road profile in the Simulink environment. The simulated results generated by using hybrid model are compared with linear model and also with the existing published results by author Demir et al. [17]. The simulated results show that hybrid shock absorber model is capable to provide the better comfort to passenger as compare to linear model. Also it has enough computational efficiency to apply in full car model to study vehicle dynamics. Hence the nonlinear and hysteresis characteristics of shock absorber must be considered in the dynamic study of vehicle.

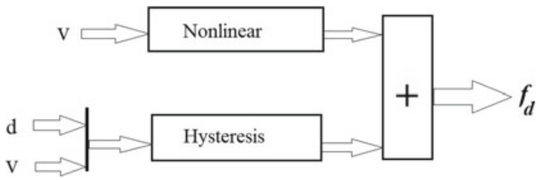


Fig. 1 Block diagram of hybrid shock absorber model

2 Hybrid Shock Absorber Model

The shock absorber is one of the most significant parts of vehicle suspension system and the typical nonlinear properties of shock absorber are complex in nature. It is very important to capture the nonlinear as well as hysteresis properties of shock absorber to study the accurate dynamics of vehicle. Most of the researchers focussed on modelling of force-velocity characteristics of shock absorber using linear, bilinear, polynomial etc. to study the performances of vehicle. In the present paper, the hybrid shock absorber model developed by Barethiye et al. [5] is used for the analysis of half car model. To build the hybrid model, author combines nonlinear force captured through piecewise linear modeling and hysteresis force obtained by Neural Network model of shock absorber to get total damping force f_d of the absorber. Figure 1 represents the block diagram of hybrid shock absorber model. The simulation of hybrid shock absorber model using mathematical equation for piecewise modeling and neural network model is carried out in Simulink software. The accuracy the hybrid model will be improved enormously as it captures effectively both nonlinear and hysteresis characteristics of the damper. To study the performances of vehicle and to predict the effect of considering the linear as well as nonlinear and hysteresis damping, the linear and hybrid shock absorber model is fed to a half car suspension system. Linear damping model considers linear damping force versus velocity relation with constant damping coefficient.

3 Modeling of 4-Degree of Freedom Half Car Suspension

3.1 Physical Set-up

A half-car model is a representation of a vehicle that consists of a body, a front wheel, and a rear wheel. The suspension assembly between the wheels includes the suspension coil spring and the damper. Figure 2 shows the schematic diagram of half car model represented as a spring-mass-damper system. The system consists of 3 mass blocks—mass of vehicle body (m_s), mass of front and rear wheels (m_{u1} and m_{u2}). The front and rear suspensions are represented by a combination of spring and damper, whereas, the stiffness of tires are represented by linear springs. The damping characteristics of tires are neglected.

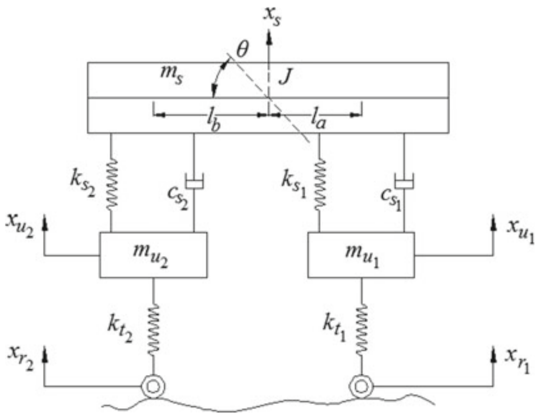


Fig. 2 Half car model for passive suspension system

3.2 Equation of Motions

The motions involved in the half car model can be clearly characterized as bouncing and pitching of the sprung mass (m_s) in addition to the vertical motions of the front and rear wheels. Here four independent coordinates (x_s, θ, x_{u1}, x_{u2}) are introduces to completely define the motion of the system. It implies that the half car system has 4 degree of freedom. From the force and moment balance equations, the governing equations of motion of the system can be derived and are presented below.

Bouncing of the sprung mass:

$$m_s\ddot{x}_s + c_{s1}(\dot{x}_{s1} - \dot{x}_{u1}) + k_{s1}(x_{s1} - x_{u1}) + c_{s2}(\dot{x}_{s2} - \dot{x}_{u2}) + k_{s2}(x_{s2} - x_{u2}) = 0 \tag{1}$$

Here $x_{s1} = l_a\theta_s + x_s$ and $x_{s2} = -l_b\theta_s + x_s$

Pitching motion of the sprung mass:

$$\begin{aligned} &J_p\ddot{\theta}_s + l_a\{c_{s1}(\dot{x}_{s1} - \dot{x}_{u1}) + k_{s1}(x_{s1} - x_{u1})\} \\ &+ l_b\{c_{s2}(\dot{x}_{s2} - \dot{x}_{u2}) + k_{s2}(x_{s2} - x_{u2})\} = 0 \end{aligned} \tag{2}$$

Front and rear wheel motion:

$$m_{u1}\ddot{x}_{u1} - c_{s1}(\dot{x}_{s1} - \dot{x}_{u1}) - k_{s1}(x_{s1} - x_{u1}) + k_{t1}(x_{u1} - x_{r1}) = 0 \tag{3}$$

$$m_{u2}\ddot{x}_{u2} - c_{s2}(\dot{x}_{s2} - \dot{x}_{u2}) - k_{s2}(x_{s2} - x_{u2}) + k_{t2}(x_{u2} - x_{r2}) = 0 \tag{4}$$

m_s	mass of the vehicle body
J_p	mass moment of inertia for the vehicle body
m_{u1}, m_{u2}	masses of the front and rear wheels respectively
c_{s1}, c_{s2}	damping coefficients of the front and rear suspensions

Table 1 Half car suspension parameter

Parameter	Values	Unit
Sprung mass of vehicle (m_s)	580	kg
Moment of inertia (J)	1100	Kgm^2
Unsprung mass of front/rear axle (m_{u1}/m_{u2})	40	kg
Spring constant of front/rear axle (k_{s1}/k_{s2})	23,500	N/m
Stiffness of the front/rear tire material (k_{t1}/k_{t2})	190	KN/m
Front body length from C.G. (l_a)	1.0	m
Rear body length from C.G. (l_b)	1.5	m
Damping front/rear suspension (c_{s1}/c_{s2})	Hybrid model (Nonlinear-hysteresis)	

k_{s1}, k_{s2} spring stiffness constant of the front and rear suspensions
k_{t1}, k_{t2} spring constants of the front and rear tires
x_s vertical displacement of the vehicle body at the centre of gravity
θ_s rotary angle of the vehicle body at the centre of gravity
x_{s1}, x_{s2} are the vertical displacements of the vehicle body at the front/rear suspension locations
x_{u1}, x_{u2} are the vertical displacements of the front and rear sprung and unsprung masses
x_{r1}, x_{r2} the irregular excitations from the road surface, and
l_a, l_b the distances of the front and rear suspension locations, with reference to the centre of gravity of the vehicle body.

The analysis is carried out, in order to compare the response of half car suspension using hybrid shock absorber model with a linear model having constant damping coefficient for bump road perturbation. The damping characteristics of shock absorber c_{s1} and c_{s2} are expressed by using hybrid shock absorber model. The important vehicle parameters [20] used for the quarter car simulation are listed along with their numerical values in Table 1.

3.3 *Road Profile for Half and Full Car Simulation*

In the present simulation study, the road profile (x_r) needs to be expressed in terms of mathematical equations and the road input to excite the half and full car models are set in the form shown below in Eq. (5).

$$x_r = \begin{cases} \frac{a\,(1-\cos(8\pi\,t))}{2} & \text{if } 1.00 \le t \le 1.25 \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

Here maximum bump amplitude is set at 0.06 m for $1.00 \le t \le 1.25$. The resulting road profile is shown in Fig. 3.

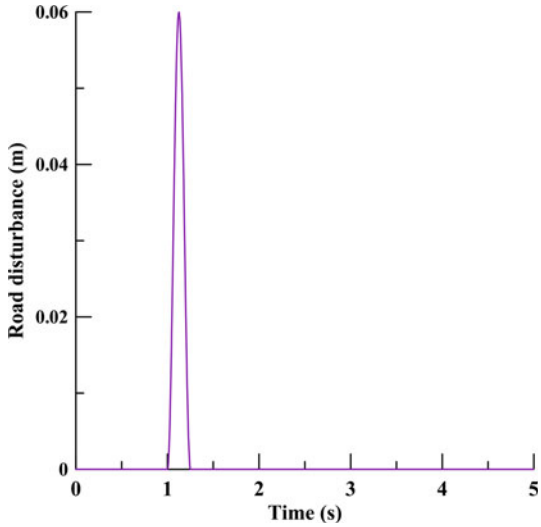


Fig. 3 Single bump road profile

3.4 Simulink Modeling for Half Car Suspension

In the present scenario a simulink plant model of car suspension system (as shown in Fig. 4) is developed incorporating linear (passive) and combined hybrid

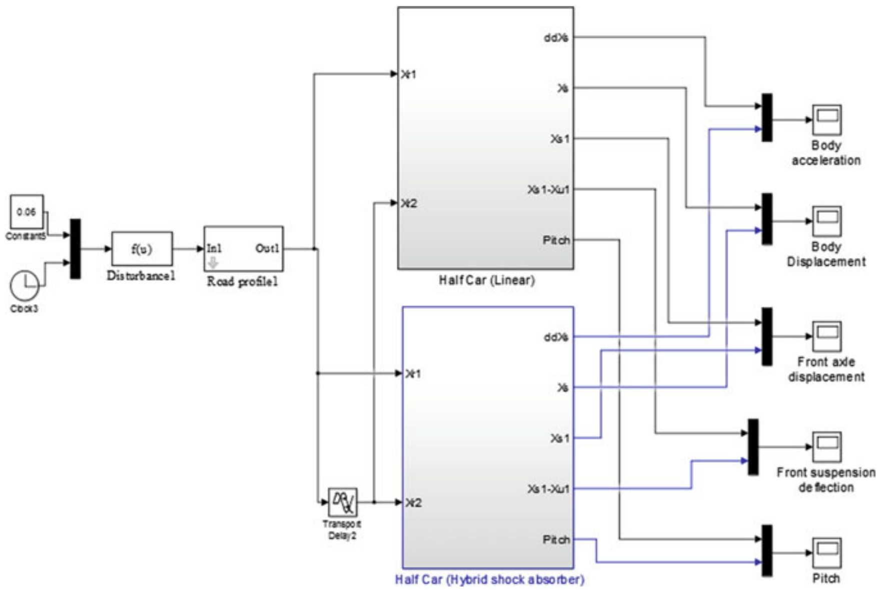


Fig. 4 Simulink model for half car system

shock (passive) absorber models. The simulations are carried out for bump road disturbances and comparative plots for the two absorber models are presented corresponding to front and rear axle displacement, vehicle body (sprung mass) displacement and pitch of the vehicle.

3.5 Results and Discussion of Half Car Model Simulation

The responses extracted from half car simulation are the vertical and angular displacement as well as vertical acceleration. Data are also obtained in terms of peak amplitude, root mean square (RMS) values and the settling time of the body in order to validate the present half car model with combined hybrid shock absorber model. The simulated results are compared with the existing published results Demir et al. [17] for bump road profile. Demir et al. [17] carried out half car model analysis in which cubic stiffness and coulomb friction are considered in suspension system and quadratic stiffness on the tire assembly.

The results from the simulation are based on the road disturbances described in Eq. 5. The main objective of this simulation is to compare the variation between linear model and hybrid shock absorber model. For the bump road perturbation, the time history of the displacement, sprung mass acceleration and the pitch angle (degree) of the half car are presented as the main results in a set of figures. The body displacement and pitch angle are indicative of the stability of vehicle after the application of road perturbation whereas body acceleration indicates the characteristic of passenger ride comfort in which the lesser magnitudes of accelerations offer a better road comfort. Another important criterion of ride comfort is the settling time.

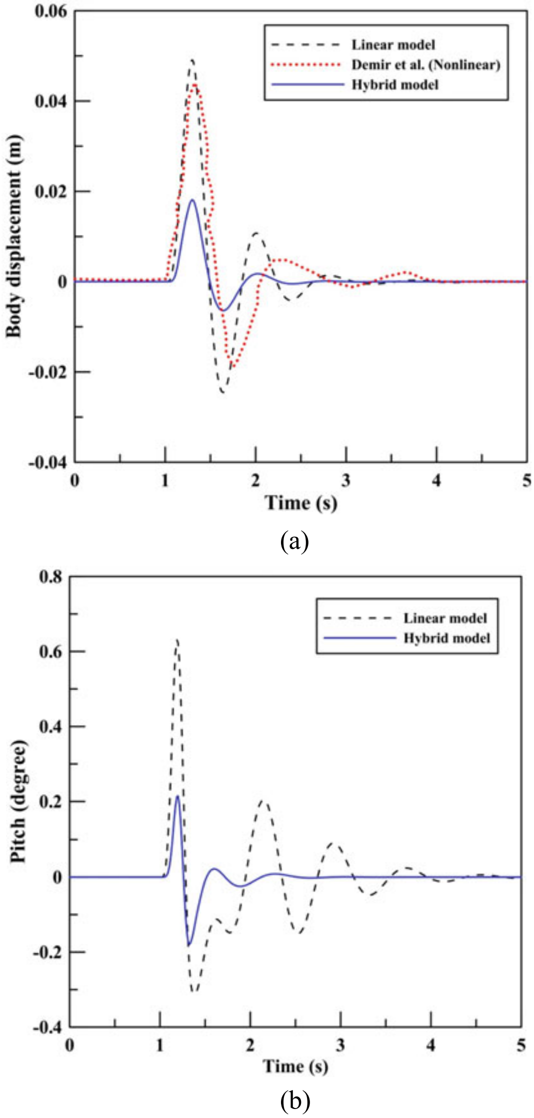
Figure 5 shows the response of the system as body displacement and pitch angle when subjected to a bump road profile. From the figure, it can be seen that there is a variation with respect to the overshoot response for both cases. The amplitude of the pitch angle for the linear damper is higher. From Fig. 5, it is observed that the settling time of oscillatory response of the hybrid shock absorber model is smaller (approximately 2.25 s) compared to the linear damper (approximately 3.5 s). Figure 6 shows the vertical acceleration measured at the center of gravity of the body when the vehicle is subjected to road disturbance. From the vertical acceleration response, it is clearly visible that a smaller acceleration (magnitude) and smaller settling time are predicted by the hybrid model as compare to the linear damper.

It needs to be pointed out that although the presented hybrid model predicts a similar nature for the responses, there is a bit of variation in the magnitude predicted as compared Demir et al. [17]. The differences may be due to the dissimilarities in modeling of the system, especially, consideration of nonlinear stiffness in the work of Demir et al. [17] and absence of hysteresis characteristics of the damper.

The response variation of front axle displacement and suspension deflection for front and rear axle are as shown in Fig. 7 and Fig. 8 respectively.

To summarise the variations in response for body acceleration, vertical displacement and pitch angle, Tables 2 and 3 present the peak amplitude values and percentage

Fig. 5 **a** Body displacement and **b** pitch angle response of the vehicle



difference of their root mean square (RMS) values. From the Tables, it shows that the response for the linear damper model is higher by 50% compared to the hybrid damper model.

For comparison purpose, the displacement and acceleration responses first peak magnitudes and RMS values are presented in Table 2 and Table 3 respectively.

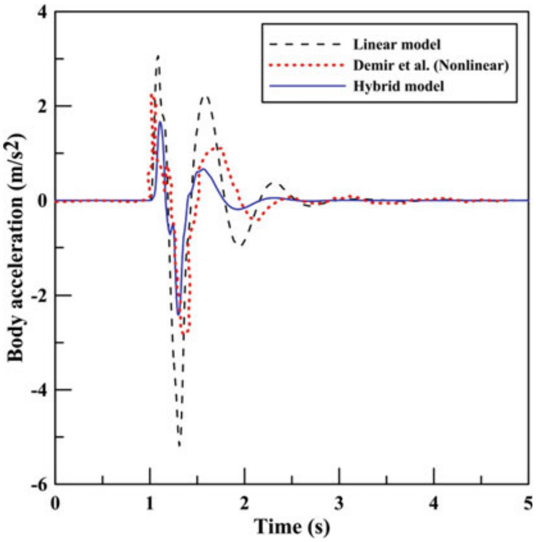


Fig. 6 Body acceleration for passive half car suspension model

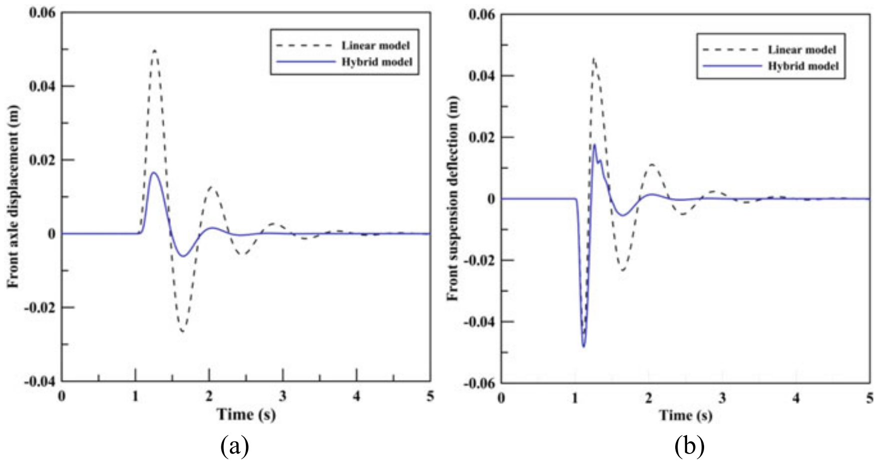
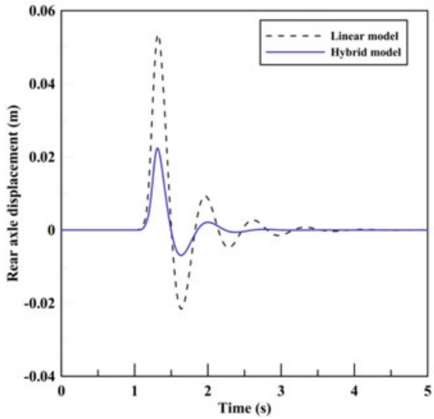


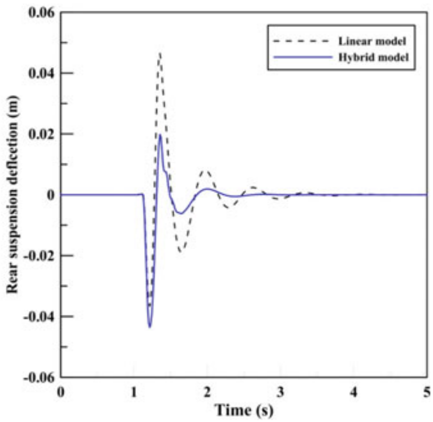
Fig. 7 **a** Front axle displacement and **b** suspension deflection of the vehicle for passive half car

4 Conclusion

The comparative analysis for the passive suspension using linear model (constant damping coefficient) and hybrid shock absorber model are presented. The influence of linear and nonlinear shock absorber damping models on vehicle characteristics are analyzed by using half car simulation. Based on the simulation analysis and



(a)



(b)

Fig. 8 **a** Rear axle displacement and **b** suspension deflection of the vehicle for passive half car

Table 2 Peak values comparison for half car passive suspension

Parameter	Unit	Linear	Passive (Hybrid model)
Body acceleration	m/s^2	3.06	1.76
Body displacement	m	0.048	0.019
Pitch angle	deg	0.608	0.21

Table 3 RMS values comparison for half car passive suspension

Parameter	Linear	Passive (Hybrid model)	Difference % (Improved)
Body acceleration (RMS)	1.263	0.527	56.23
Body displacement (RMS)	0.0165	0.0069	58.33
Pitch angle (RMS)	0.1632	0.0658	59.63

quantitative results of the half car system, the linear damping model shows the larger peak amplitude for the body acceleration, higher overshoot for displacement and pitch. Regarding settling time, the hybrid shock absorber model shows faster settling as compared to linear model. From the simulated results and statistical analysis, corresponding to body displacement, body acceleration and pitch of the vehicle, it can be concluded that the hybrid shock absorber model provides better ride comfort to passenger and also the linear damper model is inadequate to capture the vehicle performance accurately due to the absence of hysteresis force. Hence, to understand and study the performance of the vehicle the nonlinear and hysteresis properties of shock absorber must be consider. Therefore to study the dynamics of vehicle accurately the hybrid shock absorber model can be a better option as compare to linear or constant damping coefficient and piecewise linear damper.

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