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Modeling and Simulation of Semiactive and Active Suspension System using Quarter Car Model

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Abstract

A passive suspension system is used by the automotive industry to control the motion of the vehicle. Nowadays, semiactive and active suspension systems are a requirement of commercial vehicles to improve performance characteristics and road comfort. The objective of the paper is to present a comprehensive analysis of passive, semiactive, and active suspension systems. The fuzzy logic controller is used to present the active suspension system. The characteristic of the shock absorber (damper) is non-linear and hysteresis in nature. Hence, a Magneto-rheological (MR) damper-based Bouc-Wen model is utilized to present the semiactive suspension. The comparative analysis of vehicle suspension characteristics has been carried out by using a bump road profile. The modeling of the Bouc-Wen model and quarter car system is carried out in the Simulink environment. The simulated results show that the semiactive and active suspension systems can be a better option for vehicle suspension systems to provide passengers with road comfort.

Keywords: Passive; Semiactive; Active; Bouc-Wen model; Fuzzy logic; Simulink.

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1. Introduction

The purpose of the suspension system in automobiles is to improve ride comfort and road handling. The requirement for passenger comfort is to Design and develop a good suspension system with optimum vibration performance under different road conditions. The shock absorber or damper is the key element in the suspension system. It is also the least understood and most complex part of the suspension due to its non-linear and hysteresis force-velocity property [1]. Suspension control is a very difficult issue due to complicated components leading to the contradictory behavior pattern of the suspension system [2].

The semiactive control system has been proposed by many researchers, having a Magneto-rheological (MR) damper [3-5] and active suspension systems with various control techniques [6-8] to optimize vehicle performance. The study of the dynamics of a vehicle suspension is an important measure to improve the vibration problem of modern vehicles. The suspension system's main function is to decrease the vehicle's vertical

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vibration due to road perturbation and to provide passenger comfort. Therefore, the simulation and analysis of suspension control are particularly important. There are three types of suspension systems, namely, passive, semiactive, and active suspensions.

1.1. *Passive suspension*

A passive suspension system consists of a shock absorber (damper), an energy-dissipating element, and a spring, an energy-storing element. The damper and spring cannot add energy to the system; the coefficient of spring and damper is also fixed. This is called a passive suspension system [9].

1.2. *Semiactive suspension*

A semiactive suspension system combines the damping and/or the stiffness of the spring to the actual requirements. Due to low energy consumption, semi-active control is advantageous in vehicle suspension systems. Therefore, to provide passenger comfort as well as to improve vehicle handling, the semiactive suspension is introduced [9].

1.3. *Active suspension*

Active suspension systems provide an extra power input by incorporating the actuator in parallel with a shock absorber (damper) and spring. Compared to passive and semiactive control, active control suspension enables the vehicle to improve its performance while changing the road conditions and environment. However, the active suspension is disadvantageous due to the complexity and inherent cost [2,8,9].

The paper presents the modeling and simulation of the semiactive and active suspension systems to study the dynamic behavior of vehicle characteristics with the conventional passive suspension system. The Magneto-rheological (MR) damper is a type of semiactive damper in which the movement of MR fluid is controlled by altering the quantity of current and thus changing the level of damping. Therefore, in order to model the semiactive suspension, the Magneto-rheological (MR) damper characteristics using the Bouc-Wen model are implemented in the quarter car system. The fuzzy logic controller is used to present the active suspension system. The modeling and simulation have been carried out using Simulink software. The bump road profile is used as an excitation force for the quarter car model. The results section presents the comparative and quantitative analysis of simulated results for body acceleration, body displacement, and suspension deflection for the passive, semiactive, and active suspension systems.

2. System Modeling

2.1. *Quarter car*

The quarter car model of the passive and active suspension system is represented by a 2-degree-of-freedom (spring-mass-damper) system, as shown in Fig. 1 and 2, respectively.

The mass of the vehicle is represented by sprung mass m_s, and the mass of the wheel and associated components is represented by unsprung mass m_u. The vertical motions of the two masses are described by the displacement variables x_s and x_u for sprung and unsprung mass, respectively. The road excitation disturbance is given by x_r. In the quarter-car model, the suspension is located between the sprung and unsprung mass. The spring of the suspension system has stiffness k_s, whereas c_s is the constant suspension damping coefficient.
The equations of motion for the passive suspension system are given by [10];

$$m_s\ddot{x}_s + k_s(x_s - x_u) + c_s(\dot{x}_s - \dot{x}_u) = 0 \quad (1)$$

$$m_u\ddot{x}_u - k_s(x_s - x_u) - k_t(x_r - x_u) - c_s(\dot{x}_s - \dot{x}_u) = 0 \quad (2)$$

The equations of motion for an active suspension system are;

$$m_s\ddot{x}_s + k_s(x_s - x_u) + c_s(\dot{x}_s - \dot{x}_u) - f_a = 0 \quad (3)$$

$$m_u\ddot{x}_u - k_s(x_s - x_u) - k_t(x_r - x_u) - c_s(\dot{x}_s - \dot{x}_u) + f_a = 0 \quad (4)$$

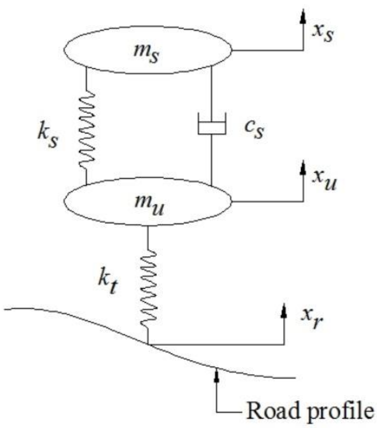


Fig. 1. Passive suspension system.

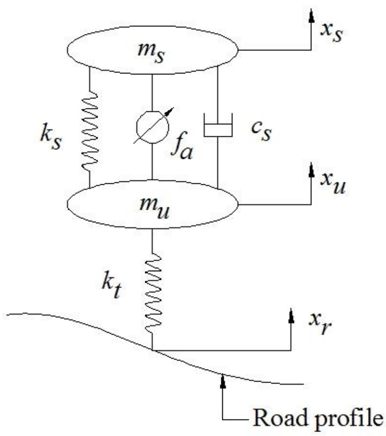


Fig. 2. Active suspension system.

2.2. ***Semiactive feedback control of quarter car model using MR Damper***

The vibration of the vehicle can be reduced by using a semiactive suspension, in which the damping coefficient of the shock absorber can be changed by using a semiactive control system. Nowadays, the Magneto-rheological (MR) damper is used as a semiactive device to improve road comfort in which the movement of MR fluid is controlled by altering the quantity of current and thus changing the level of damping. The Bouc–Wen model [11,12] is used to implement the damper into a variable condition to develop semiactive control for an MR damper. Such characteristics using a proposed model were first introduced by Bouc (1967) and later modified by Wen (1976). The Bouc-Wen model represents a large class of hysteretic behavior varying from inelastic stress-strain relationships to magneto-rheological behavior. It is used to describe the force displacement and force-velocity behavior of MR dampers. The simple form of the Bouc-Wen model for MR damper can be described in Fig. 3. The damping force in the system can be written as;

$$F = c_o\dot{x} + k_o(x - x_o) + \alpha z \tag{5}$$

where, c_o and k_o represent the viscous and stiffness coefficients, respectively, x_o represents the initial displacement of the spring, and z represents the variable related to the Bouc-Wen block and given by;

$$\dot{z} = -\gamma|\dot{x}|z|z|^{n-1} - \beta\dot{x}|z|^n + A\dot{x} \tag{6}$$

Finally, it is noted that the simple Bouc-Wen model described by Eq. (5) and Eq. (6) is well suited for the numerical simulation and can be used to describe the non-linear force versus displacement. The parametersc_o, k_o, α, β, γ, n, and A are usually called characteristic or shape parameters of the Bouc–Wen model and are functions of the current, amplitude, and frequency of excitation.

In this analysis, a simple quarter car model with MR damper is shown in Fig. 3. The MR damper characteristics using the Bouc-Wen model are used as a semiactive control, and the parameter values for the quarter car system are presented in Table 1.

Table 1. Quarter car parameter.

Sl. No.	Parameter	Value	Unit
1	Sprung mass	300	Kg
2	Unsprung mass	50	Kg
3	Suspensión stiffness	17600	N/m
4	Tyre stiffness	200000	KN/m
5	Damping Coefficient	1000	Ns/m

Whereas the parameters for the Bouc-Wen model [13-14] are the parameter of hysteretic shape (*β, γ,* A, n), Stiness of the spring element (k_0), and other parameters (c_{0a}, c_{0b}, α_{0a}, α_{ob}) is given as follows,

$\beta = 0.647\ m^{-1}$ $\gamma = 0.647 m^{-1}$ $A = 2.68\ m^{-1}$ $n = 10$

$k_0 =$ 620 N/m

$c_{0a} = 780$ Ns/m $c_{0b} = 1800$ Ns/V $\alpha_{0a} = 12440$ N/m $\alpha_{ob} = 38430$ N/m

The equation of motion can be written as follows;

$$m_s\ddot{x}_s + k_s(x_s - x_u) + c_0(\dot{x}_s - \dot{x}_u) = -\alpha z \tag{7}$$

$$m_u\ddot{x}_u - k_s(x_s - x_u) - k_t(x_r - x_u) - c_0(\dot{x}_s - \dot{x}_u) = \alpha z \tag{8}$$

where the variable z is governed by;

$$\dot{z} = -\gamma|(\dot{x}_s - \dot{x}_u)|z|z|^{n-1} - \beta(\dot{x}_s - \dot{x}_u)|z|^n + A(\dot{x}_s - \dot{x}_u) \tag{9}$$

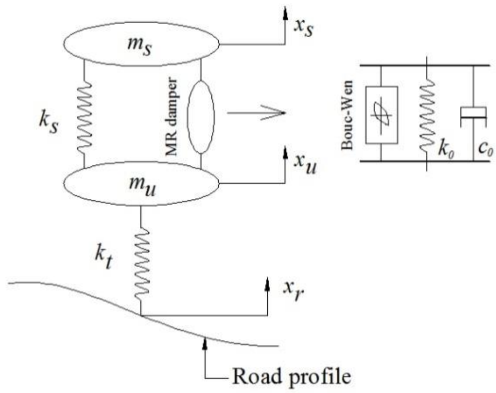
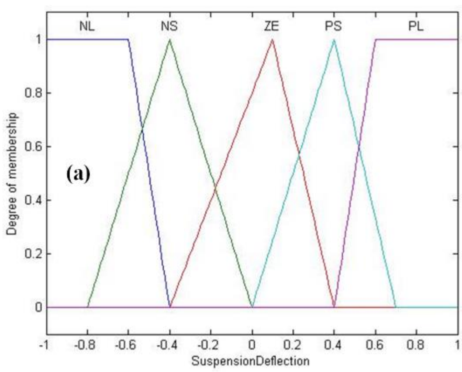


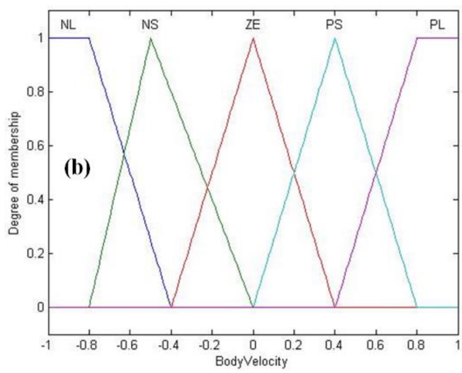
Fig. 3. Semiactive suspension system (using Bouc-Wen model).

3. Fuzzy Logic Control

The fuzzy logic control system consists of three stages: fuzzification, fuzzy inference machine, and defuzzification. The fuzzification stage converts real-number (crisp) input values into fuzzy values, while the fuzzy inference machine processes the input data and computes the controller outputs to cope with the rule base. These outputs, which are fuzzy values, are converted into real numbers by the defuzzification stage.

The fuzzy logic control used in the present active suspension system has two inputs, namely, body velocity and suspension deflection, and one output, which is the desired actuator force. A possible choice of the membership functions for the three mentioned variables of the active suspension system represented by a fuzzy set is shown in Fig. 4 (a), (b), and (c). The rule base parameters [8] for the control system are shown in Table 2. The trial-and-error method is used to tune the fuzzy controller's scaling factor to minimize the vehicle acceleration.





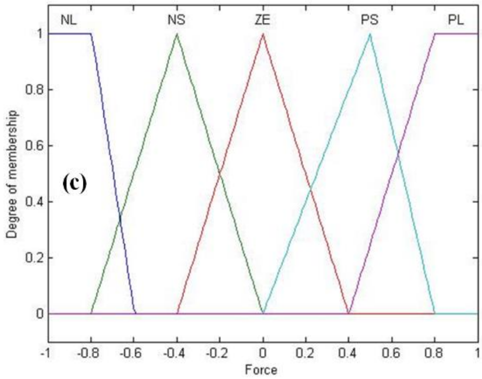


Fig. 4. (a) Membership function for velocity input, (b) for suspension deflection input, (c) for force output.

Table 2. Rule base.

Velocity	Suspension deflection				
	NB	NS	ZE	PS	PB
NB	PB	PB	PS	PS	ZE
NS	PB	PS	PS	ZE	NS
ZE	PS	PS	ZE	NS	NS
PB	PS	ZE	NS	NS	NB
PB	ZE	NB	NS	NB	NB

4. Simulink Modeling and Analysis

Simulink is widely known to be a useful tool to model linear and non-linear quarter car systems and subsequently capture their dynamic responses [1,10]. The quarter car modeling for passive semiactive using the Bouc-Wen model (Fig. 5) and active suspension using a fuzzy controller (Fig. 6) with Simulink software has been carried out to compare the performances of the vehicle.
The single bump and two bump road profiles are used for road excitation [15-16].

$$x_r = \begin{cases} \dfrac{a(1-\cos(8\pi t))}{2} & \text{if} \quad 0.50 \le t \le 0.75 \quad \text{and} \\ 0 & \text{otherwise} \end{cases}$$

Where a denotes the maximum bump amplitude which is set to be 10 cm for 0.5 ≤ t ≤ 0.75.

$$x_r = \begin{cases} \dfrac{a(1-\cos(8\pi t))}{2} & \text{if} \quad 0.50 \le t \le 0.75 \quad \text{and} \\ & 3.00 \le t \le 3.25 \\ & 0 \quad \text{otherwise} \end{cases}$$

Where *a* denotes maximum bump amplitude, which is set to be 11 cm for 0.5 ≤ t ≤ 0.75 and 5.5 cm for 3.00 ≤ t ≤ 3.2.

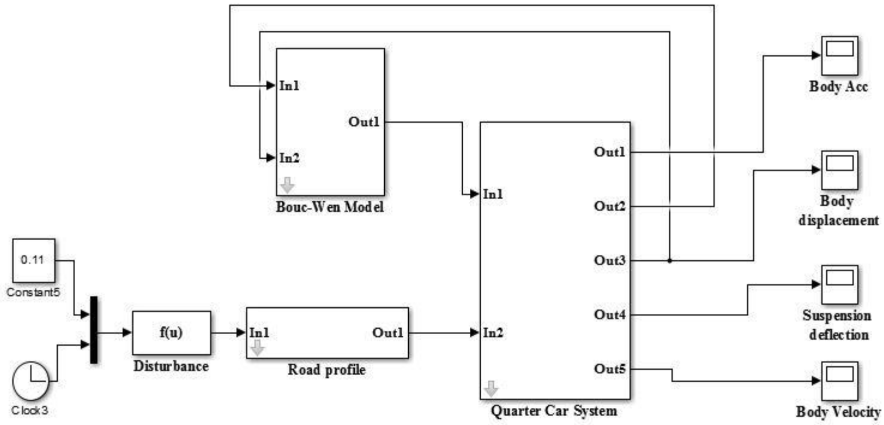


Fig. 5. Semiactive suspension system (using Bouc-Wen model).

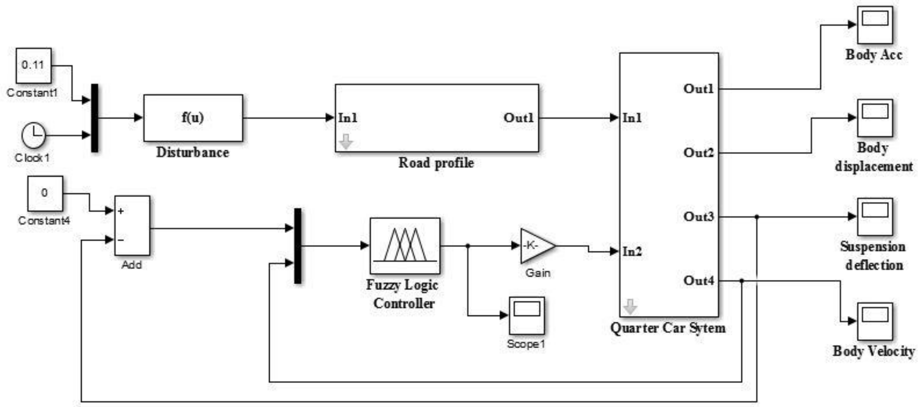


Fig. 6. Active suspension system.

5. Results and Discussion

This work compares the performances of the passive, semiactive, and active suspension systems. The Active suspension system has been controlled by using the Fuzzy Logic controller. The results obtained for active suspension using fuzzy control are compared and validated with the results of Agharkakli *et al.* [16] for suspension deflection and wheel displacement using single bump perturbation. The comparisons are shown in Figs. 7 and 8. The results of the active suspension using a fuzzy controller show good agreement with that of the results obtained by Agharkakli *et al.* [16] for active suspension using the Linear-Quadratic-Regulator (LQR) controller technique.

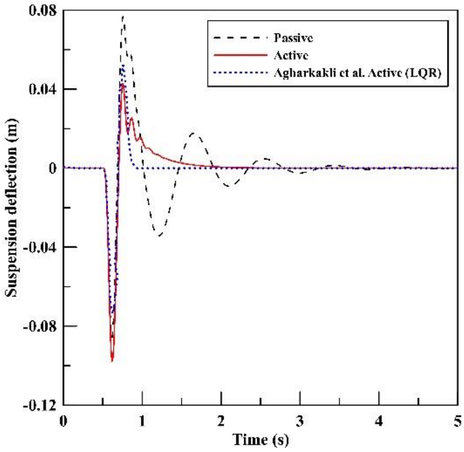


Fig. 7. Suspension deflection.

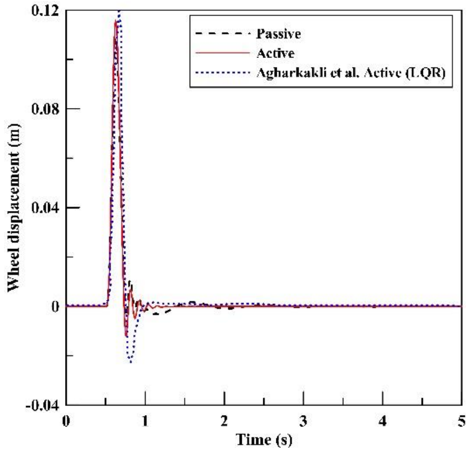


Fig. 8. Wheel displacement

The performance of active suspension using a fuzzy controller and semiactive suspension using a feedback control technique are compared with passive suspension using quarter car simulation.

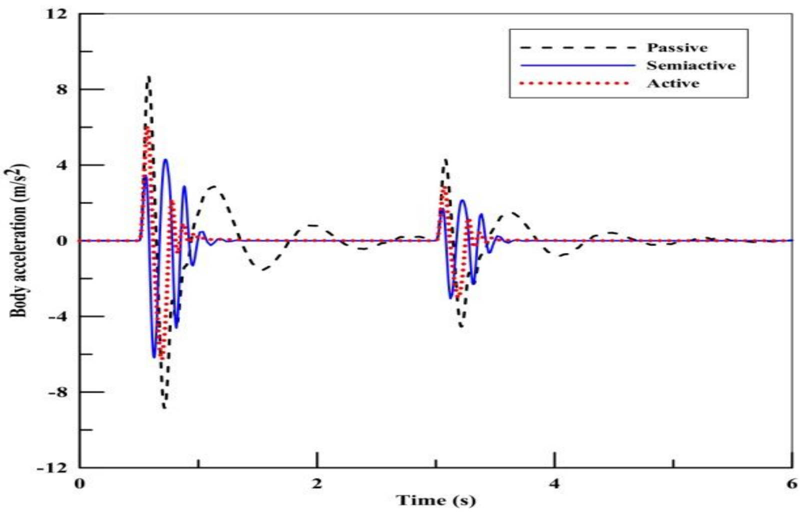


Fig. 8. Body acceleration.

The results obtained for body acceleration, suspension deflection, and displacement are shown in Figs. 8, 9, and 10, respectively. Also, the statistics for the vehicle performance in terms of RMS value and Peak value are presented in Table 3.

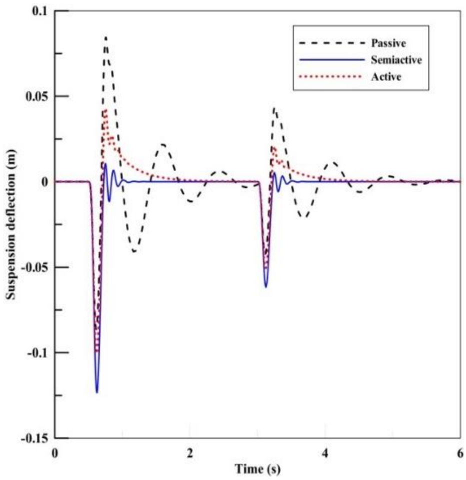


Fig. 9. Suspension deflection.

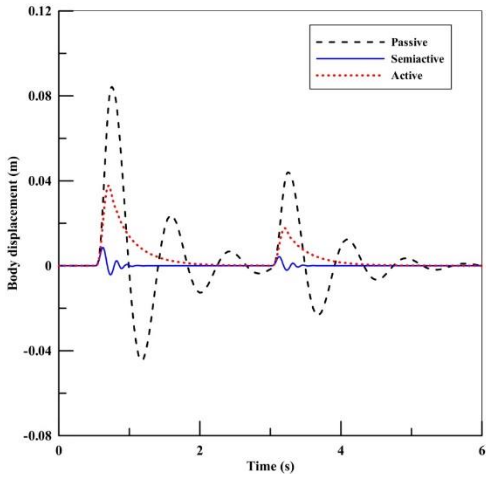


Fig. 10. Body displacement.

Table 3. Statistics for vehicle characteristics.

Sl. No.	Parameter	Unit	Passive	Semiactive	Active
1	Peak body acceleration	m/s^2	8.7197	4.3055	6.0417
2	Body acceleration (RMS)	m/s^2	4.6358	2.3552	2.9911
3	Peak body displacement	m	0.0842	0.0086	0.0377
4	Body displacement (RMS)	m	0.0440	0.0027	0.0211
5	Peak suspension deflection	m	0.0844	0.0106	0.0429
6	Suspension deflection (RMS)	m	0.0419	0.0406	0.0429

The following observations are made based on simulation results (Figs. 8-10) and statistical data (Table 3).

- The peak and RMS value of body acceleration of the semiactive and active suspension systems is smaller than the passive suspension.
- The peak and RMS value body displacement for semiactive suspension and active suspension systems are smaller than for passive suspension.
- The RMS value of suspension deflection for the active suspension exhibits a larger value, whereas the peak suspension deflection value for the semiactive suspension and active suspension system is found to be smaller than the passive suspension. From the established simulated results and comparative statistics of vehicle characteristics, it can be observed that active suspension using fuzzy logic control can give a lower amplitude and faster settling time over the passive suspension, which eventually improves ride comfort.

6. Conclusion

The quarter car simulation and analysis for passive, semiactive, and active suspension systems using fuzzy logic control has been carried out for bump road excitation. The semiactive suspension system is a feedback control system by using a Magneto-rheological damper. The simulated result of the body acceleration, body displacement, and suspension deflection show that the amplitude of semiactive and active suspension improves the performances of the vehicle as compared to the passive suspension. It is also apparent that the settling time is quite large for the passive suspension system compared to the semiactive and active suspension systems. The results of semiactive suspension are lower in amplitude than the active suspension due to using a Magneto-rheological damper. The semiactive suspension can also be developed for hydraulic dampers using various control systems. Therefore, semiactive and active suspension can be a better option to provide passenger comfort and road handling.

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