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Fuzzy-Skyhook Control for Active Suspension Systems Applied to a Full Vehicle Model

Aref M.A. Soliman[1,*], Mina M.S. Kaldas[2], David C. Barton[3] and Peter C. Brooks[3]

[1]Department of Mechanical Engineering, South Valley University, Egypt.

[2]Institute of Automotive Engineering, TU Braunschweig, Germany.

[3]Institute School of mechanical Engineering, Leeds University, Leeds, UK.

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Abstract

Nowadays, most modern vehicles are equipped with controlled suspension systems for improving the vehicle ride comfort. Therefore, this paper is concerned with a theoretical study for the ride comfort performance of the vehicle. The theoretical investigation includes a suggestion of an active suspension system controller using fuzzy-skyhook control theory, which offers new opportunities for the improvement of vehicle ride performance. The ride comfort of the active suspension system has been evaluated using a 7 degree of freedom full vehicle mathematical model. The simulation results are presented in the time and frequency domain, also in terms of RMS values, and it’s shown that the proposed active suspension system with fuzzy-skyhook control improved the vehicle ride quality in terms of body acceleration, suspension working space and dynamic tyre load in comparison with the passive and skyhook suspension systems.

Keywords: Active suspensions, fuzzy control, skyhook control, fuzzy-skyhook control, full vehicle model, ride comfort

1. Introduction

The active suspension of ground vehicles is a very active subject for research owing to its potential to improve the vehicle ride performance. Many analytical and experimental studies performed recently have been concluded that the active suspension can in general provide substantial performance improvements over optimized passive suspensions [1, 2, 3, 4, 5 and 6]. Using Fuzzy-Logic control in a simple form with the active suspension system applied to a quarter vehicle model is studied theoretically by [7]. [7] evaluated the ride performance under various road inputs. The simulation results indicated a great enhancement in the ride performance in terms of body acceleration and suspension working space for different road inputs.

[8] presented a more complex active suspension system controller using fuzzy reasoning and a disturbance observer applied to a quarter vehicle model. The active control force is released by actuating a pneumatic actuator. The excitation from the road profile is estimated by using a disturbance observer, and denoted as one of the variables in the precondition part of the fuzzy control rules. The experimental result indicated that the proposed active suspension system controller improved the vibration suppression of the vehicle model. Adaptive fuzzy logic (AF) and active force control (AFC) strategies are applied to a quarter vehicle model by [9]. They proposed a control system which essentially comprises three feedback control loops.

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* Corresponding author. E-mail address: arefsoliman@gmail.com
Tel.: +2-01005859571; Fax: +2(096)5211279

The first loop is the innermost control loop (PI) for tracking the hydraulic actuator force. The second one is called the intermediate active force control loop (AFC) for compensating the disturbances and the third one is the outermost adaptive fuzzy control loop (AF) for computing the optimum target command force. The simulation results showed that the active suspension system with adaptive fuzzy active force control (AF-AFC) yields superior performance when compared to the AF system without AFC as well as to the passive suspension system.

In more detailed studies, [10] developed a fuzzy logic control for an active suspension system applied to a half vehicle model. The velocity and the acceleration of the front and rear wheels, and undercarriage velocity above the front and rear wheels are considered as controller input signals. The results showed that an achievement in ride and handling is obtained relative to a traditional passive suspension system. Using linear control together with fuzzy logic control in an active suspension system was investigated by [11]. In this paper the active control is the sum of two kinds of control. The former is obtained by vertical acceleration of the vehicle body as the principal source of control, and the latter is obtained by using fuzzy logic control as a complementary control. The simulation results indicate that, the proposed active suspension system is very effective in the vibration isolation of the vehicle body. [12] Prepared a theoretical investigation for an active suspension system applied to a full passenger car model. An active suspension system controller based on fuzzy logic control was designed. The sprung mass velocity and unsprung mass velocity were considered as controller inputs. The results indicated that fuzzy logic control of an active suspension system provides a significant improvement in comparison with passive suspension systems and LQR active suspension systems. Since investigating the interaction between the active suspension and the anti-lock braking systems is also important, [13] suggested a fuzzy logic controller for an active suspension system applied to a half vehicle model. The active suspension system, tyre-road interface and anti-lock braking system were included in the model. The body acceleration and suspension working space were used as controller inputs. From the simulation results, they concluded that fuzzy logic control with active suspension system improved the vehicle ride performance when compared with passive systems. Furthermore, as studying the interaction between the suspension and braking systems for heavy vehicles, [14] suggested fuzzy logic controllers for three axles long chassis truck active suspension and cab suspension systems together with anti-lock braking system and integrated control system. The results showed that fuzzy logic control with active truck suspension and cab suspension improved the truck ride comfort; also using it with anti-lock braking system enhanced the braking performance of the truck at different driving condition. Furthermore, the proposed integrated control improved the ride comfort of the truck during braking process.

In this paper, a theoretical study of the ride comfort behaviour of an actively suspended vehicle is presented. Furthermore, an active suspension system controller based on fuzzy-skyhook control has been suggested to implement a new sort of active suspension system controller. The simulation utilizes a 7-degree of freedom full vehicle model and the ride comfort performance has been evaluated via the body vertical acceleration, suspension working space and dynamic tyre load.

2. Road Input

A sinusoidal shape of road profile was used consisting of two successive bumps of height *h* = 0.05 m for the left track and 0.08 m for the right track with a wave length λ = 20 m and vehicle velocity *v* = 20 m/s [15]. As a function of time, the road conditions are given by the following:

$$X_{o1,3}(t) = \begin{cases} \frac{h}{2} \cdot (1 - \cos(wt)) & 0 \le t \le (\frac{2\lambda}{v}) \\ 0 & Otherwise \end{cases} \tag{1}$$

$$X_{o2,4}(t)=\begin{cases}\dfrac{h}{2}\cdot(1-\cos(w\cdot(t+\tau))) & \tau\le t\le(\tau+\dfrac{2\lambda}{v}) \\ 0 & Otherwise\end{cases} \tag{2}$$

$$\tau=\frac{L_1+L_2}{v} \tag{3}$$

$$w=\frac{2\cdot\pi\cdot v}{\lambda} \tag{4}$$

This road input will help to introduce bounce, pitch and roll motion simultaneously. The resulting road input profile used in this study is shown in Fig. 1.

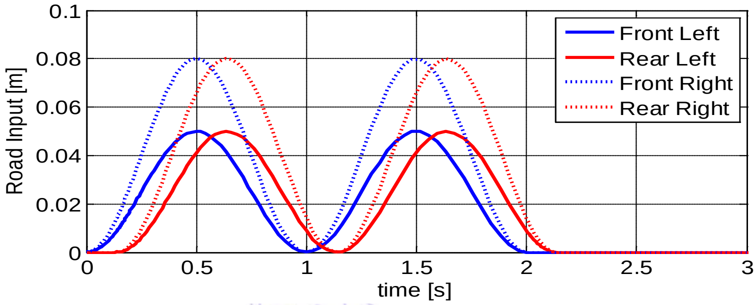

Fig. 1 Road profile

3. Vehicle Mathematical Model

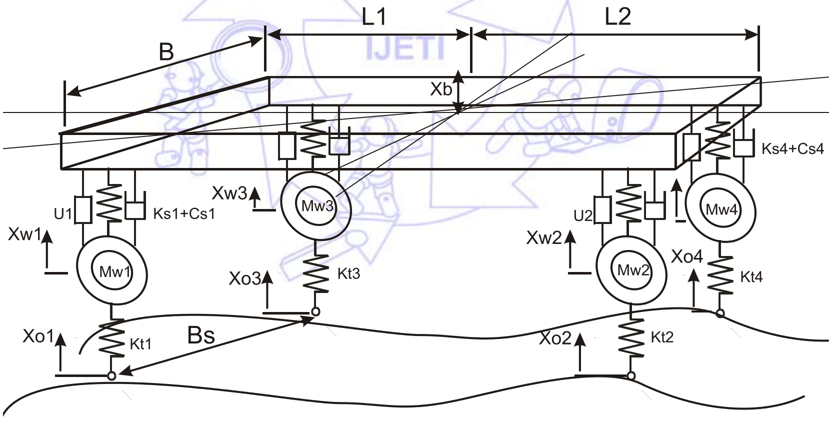

Fig. 2 the 7- degree of freedom full vehicle model

Fig. 2 shows the full vehicle model used in this study. The passive suspension system between the sprung mass and unsprung masses was modeled as a linear spring and viscous damper at each corner. On the other hand, the active system uses their components coupled with a linear actuator. The tyre is modeled as a linear spring only without damping. The equations of motion for body vertical, pitch and roll motions are given as follow:

$$\begin{aligned}M_b\cdot\ddot{X}_b = &-K_{s1}(X_{b1}-X_{w1})-C_{s1}(\dot{X}_{b1}-\dot{X}_{w1})-K_{s2}(X_{b2}-X_{w2})-C_{s2}(\dot{X}_{b2}-\dot{X}_{w2}) \\ &-K_{s3}(X_{b3}-X_{w3})-C_{s3}(\dot{X}_{b3}-\dot{X}_{w3})-K_{s4}(X_{b4}-X_{w4})-C_{s4}(\dot{X}_{b4}-\dot{X}_{w4}) \\ &+U_{s1}+U_{s2}+U_{s3}+U_{s4}\end{aligned} \tag{5}$$

$$\begin{aligned}I_b\cdot\ddot{\theta}_b = &\; L_1K_{s1}(X_{b1}-X_{w1})+L_1C_{s1}(\dot{X}_{b1}-\dot{X}_{w1})+L_1K_{s3}(X_{b3}-X_{w3})+L_1C_{s3}(\dot{X}_{b3}-\dot{X}_{w3}) \\ &-L_2K_{s2}(X_{b2}-X_{w2})-L_2C_{s2}(\dot{X}_{b2}-\dot{X}_{w2})-L_2K_{s4}(X_{b4}-X_{w4})-L_2C_{s4}(\dot{X}_{b4}-\dot{X}_{w4}) \\ &-L_1U_{s1}-L_1U_{s3}+L_2U_{s2}+L_2U_{s4}\end{aligned} \tag{6}$$

$$\begin{aligned} I_{br}\cdot\ddot{\phi}_b = & \frac{Bs}{2}K_{s1}(X_{b1}-X_{w1})+\frac{Bs}{2}C_{s1}(\dot{X}_{b1}-\dot{X}_{w1})+\frac{Bs}{2}K_{s2}(X_{b2}-X_{w2})+\frac{Bs}{2}C_{s2}(\dot{X}_{b2}-\dot{X}_{w2}) \\ & -\frac{Bs}{2}K_{s3}(X_{b3}-X_{w3})-\frac{Bs}{2}C_{s3}(\dot{X}_{b3}-\dot{X}_{w3})-\frac{Bs}{2}K_{s4}(X_{b4}-X_{w4})-\frac{Bs}{2}C_{s4}(\dot{X}_{b4}-\dot{X}_{w4}) \\ & -\frac{Bs}{2}U_{s1}-\frac{Bs}{2}U_{s2}+\frac{Bs}{2}U_{s3}+\frac{Bs}{2}U_{s4} \end{aligned} \tag{7}$$

$$X_{b1} = X_b + L_1\cdot\theta_b + \frac{B_s}{2}\cdot\phi b \tag{8}$$

$$X_{b2} = X_b + L_2\cdot\theta_b + \frac{B_s}{2}\cdot\phi b \tag{9}$$

$$X_{b3} = X_b + L_1\cdot\theta_b + \frac{B_s}{2}\cdot\phi b \tag{10}$$

$$X_{b4} = X_b + L_2\cdot\theta_b + \frac{B_s}{2}\cdot\phi b \tag{11}$$

$$M_{w1}\cdot\ddot{X}_{w1} = -K_{t1}(X_{w1}-X_{o1})+K_{s1}(X_{b1}-X_{w1})+C_{s1}(\dot{X}_{b1}-\dot{X}_{w1})-U_{s1} \tag{12}$$

$$M_{w2}\cdot\ddot{X}_{w2} = -K_{t2}(X_{w2}-X_{o2})+K_{s2}(X_{b2}-X_{w2})+C_{s2}(\dot{X}_{b2}-\dot{X}_{w2})-U_{s1} \tag{13}$$

$$M_{w3}\cdot\ddot{X}_{w3} = -K_{t3}(X_{w3}-X_{o3})+K_{s3}(X_{b3}-X_{w3})+C_{s3}(\dot{X}_{b3}-\dot{X}_{w3})-U_{s3} \tag{14}$$

$$M_{w4}\cdot\ddot{X}_{w4} = -K_{t4}(X_{w4}-X_{o4})+K_{s4}(X_{b4}-X_{w4})+C_{s4}(\dot{X}_{b4}-\dot{X}_{w4})-U_{s4} \tag{15}$$

4. Fuzzy- Skyhook Control Theory

The skyhook system is considered the ideal system in ride comfort performance of the vehicle suspension system because it is able to reduce the ride comfort performance criteria to the smallest allowable values. Fuzzy logic control (FLC) is one of intelligent control methods. FLC offers several unique features that make it a particularly good choice for many control problems; also it can control nonlinear systems that would be difficult or impossible to model mathematically.

FLC does not require precise, noise-free inputs and can be programmed to fail safely if a feedback sensor fails or is destroyed. Furthermore, the output control signal is a smooth control function despite a wide range of input variations. Therefore, any sensor data that provides some indication of system actions and reactions is sufficient. This allows the sensors to be inexpensive and imprecise and reduce the overall system cost and complexity [16 and 17].

In this paper, fuzzy logic control theory is used to construct an active suspension system controller for a full vehicle model. The controller uses the body vertical, pitch and roll accelerations as inputs. The generated output signal is the desired actuator force at each corner. The rule base and the interface engine are based on Mamdani-Type of fuzzy inference, while the defuzzification process is based on centre of area method [13 and 14]. The surface view of the fuzzy logic controller of the active suspension system is shown in Fig. 3.

The idea of the fuzzy-skyhook control strategy is to use the skyhook model to generate the ideal performance criteria (body vertical and pitch and roll accelerations) of the full vehicle suspension system model. However, the actual ride comfort performance criteria are generated by the active suspension system model. Therefore, the control unit compares the feedback signals of the actual performance criteria of the active suspension system model with the skyhook model signals and computes the error between the actual signals and the ideal signals.

The fuzzy logic controller of the active suspension system uses the actual signals of the ride comfort performance parameters and the computed error signals as controller inputs. As a result of the control process of the fuzzy logic controller generates the desired actuator force at each corner. The control strategy is shown schematically in Fig. 4.

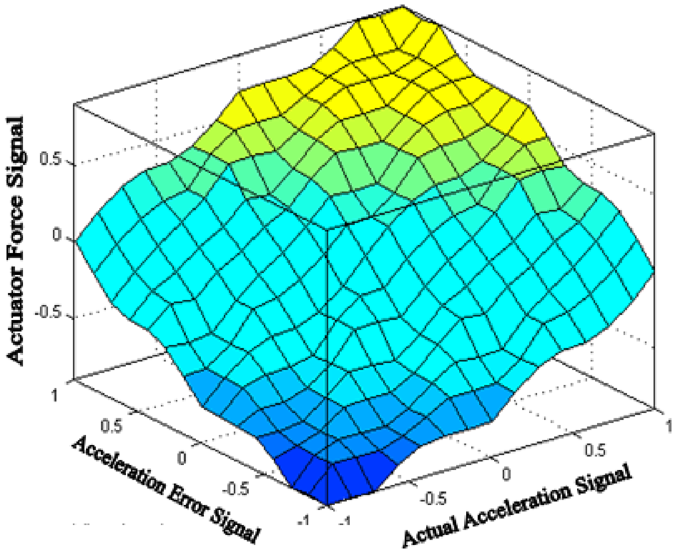

Fig. 3 the surface view of the fuzzy logic controller

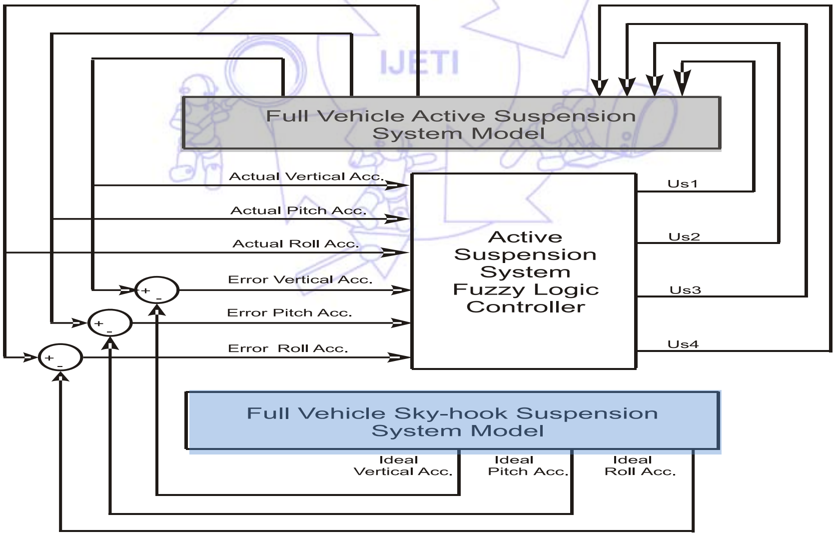

Fig. 4 over view of the control strategy

5. Simulation and Vehicle Parameters

The numerical model was implemented in MatLab/SIMULINK to evaluate the full vehicle ride performance. The results are expressed in the time and frequency domain and in terms of root mean square values. The vehicle parameters used in this model can be seen in Table 1.

Table 1 used vehicle parameters

Parameter	**Definition**	**Value**	**Unit**
M_b	Body Mass	1400	kg
$M_{w1,3}$	Left wheel masses	50	kg
$M_{w2,4}$	Right wheel masses	55	kg
I_b	Body pitch moment of inertia	2500	kg.m²
I_{br}	Body roll moment of inertia	400	kg.m²
$K_{s1,3}$	Left spring stiffnesses	20	kN/m
$K_{s2,4}$	Right spring stiffnesses	25	kN/m
$K_{t1,2,3,4}$	Tyre stiffnesses	200	kN/m
$C_{1,3}$	Left damping coefficients	1500	kN.s/m
$C_{2,4}$	Right damping coefficients	1900	kN.s/m
L_1	Distance from front axle to C.G	1.25	m
L_2	Distance from rer axle to C.G	1.5	m
B_s	Wheel track	1.5	m

6. Results and Discussion

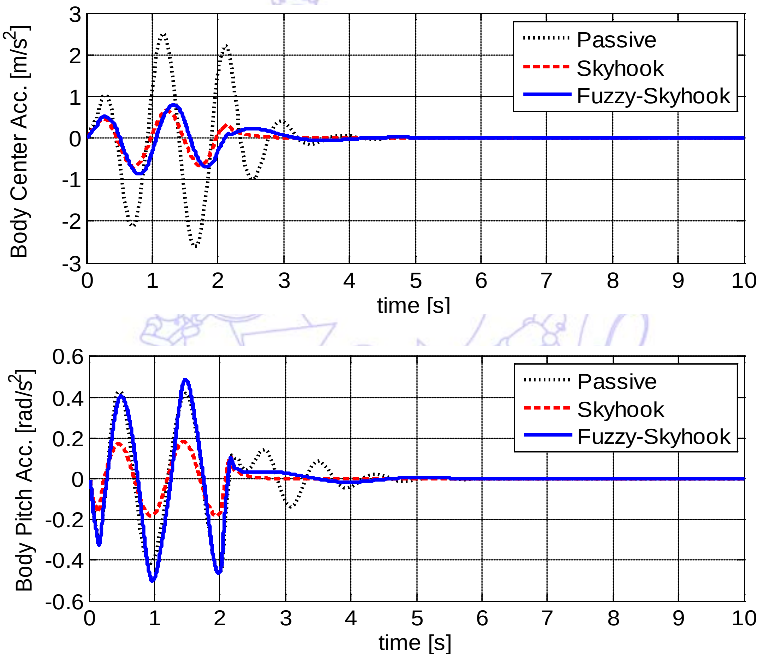

Fig. 5 Comparison between the body center and pitch accelerations of the passive, skyhook and active fuzzy-skyhook suspension systems

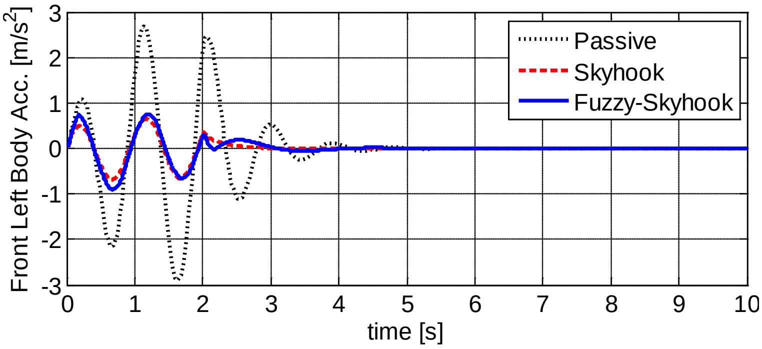

Fig. 6 Comparison between the passive, skyhook and active fuzzy-skyhook suspension systems in terms of body vertical acceleration at each corner (continued)

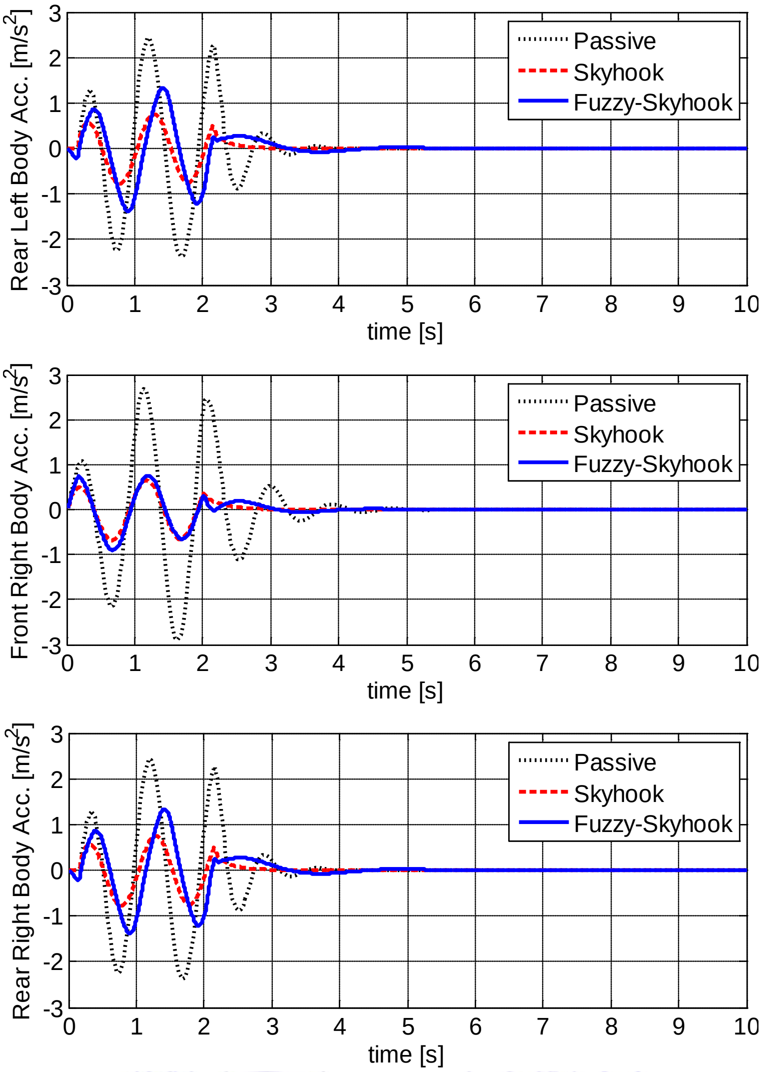

Fig. 6 Comparison between the passive, skyhook and active fuzzy-skyhook suspension systems in terms of body vertical acceleration at each corner

Fig. 5 shows comparisons between the body centre and pitch accelerations for passive, skyhook and active fuzzy-skyhook suspension systems. From this figure, it can be clearly seen that, a great improvement in body centre acceleration is obtained when the suggested fuzzy-skyhook active suspension system controller is used; the pitch acceleration is improved. Fig. 6 shows the time histories of the body vertical acceleration at each corner for passive, skyhook and active fuzzy-skyhook suspension systems. The time range of 10 seconds is chosen to illustrate the peaks of body and wheel. It can be seen that when the suggested active suspension system controller is used, the peaks of body acceleration are reduced approximately to the ideal skyhook system.

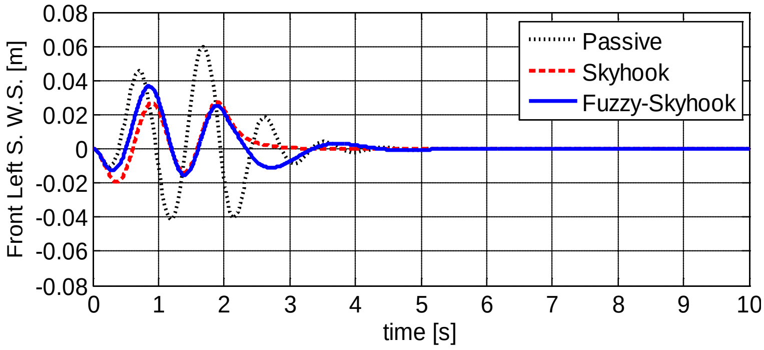

Fig. 7 Comparison between the passive, skyhook and active fuzzy-skyhook suspension systems in terms of suspension working space at each corner (continued)

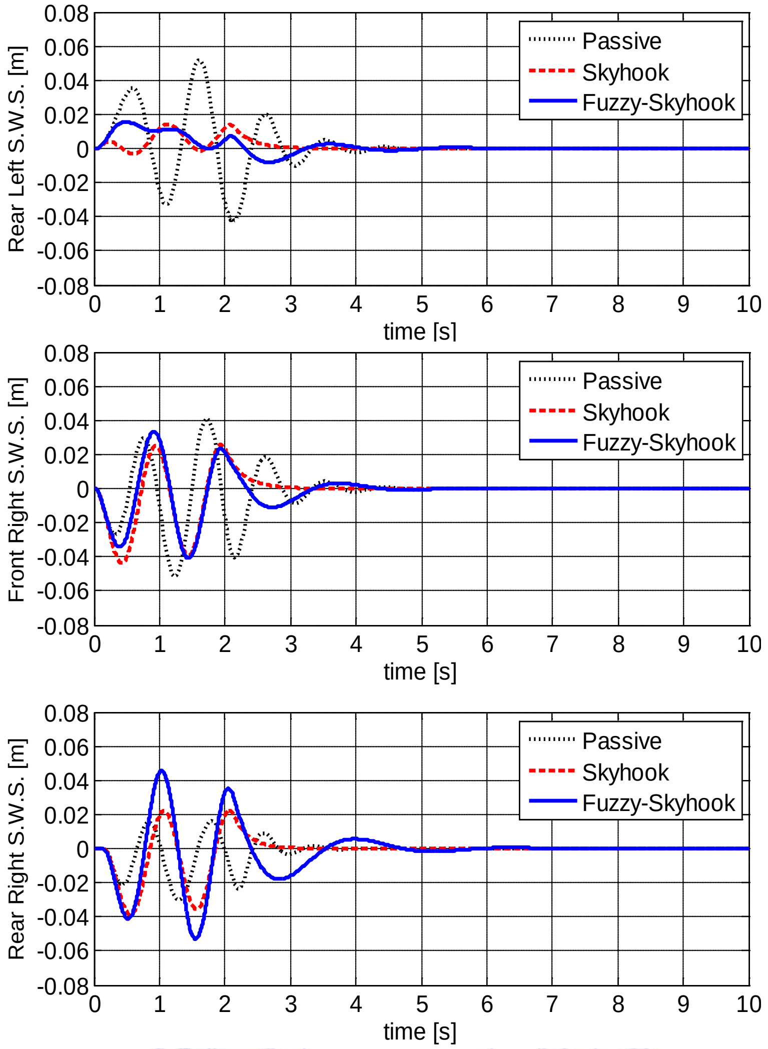

Fig. 7 Comparison between the passive, skyhook and active fuzzy-skyhook suspension systems in terms of suspension working space at each corner

The time histories of suspension working space at each corner of the passive, skyhook and active fuzzy-skyhook suspension systems are shown in Fig. 7. It can be seen that using fuzzy-skyhook control with the active suspension system improved the suspension working space approximately for all wheels, and this improvement can also be seen in terms of root mean square in Table 2.

Fig. 8 shows the time histories of the dynamic tyre load at each corner for passive, skyhook and active fuzzy-skyhook suspension systems. It can be seen that the fuzzy-skyhook controller with the active suspension system keeps the dynamic tyre load approximately constant around the passive suspension system as a result of the great improvement in body accelerations.

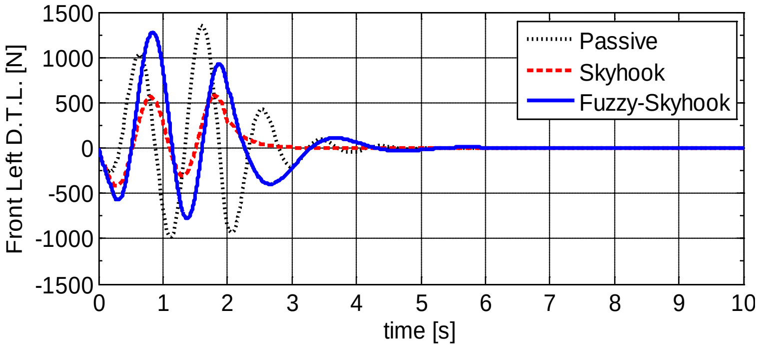

Fig. 8 Comparison between the passive, skyhook and active fuzzy-skyhook suspension systems in terms of dynamic tyre load at each corner (continued)

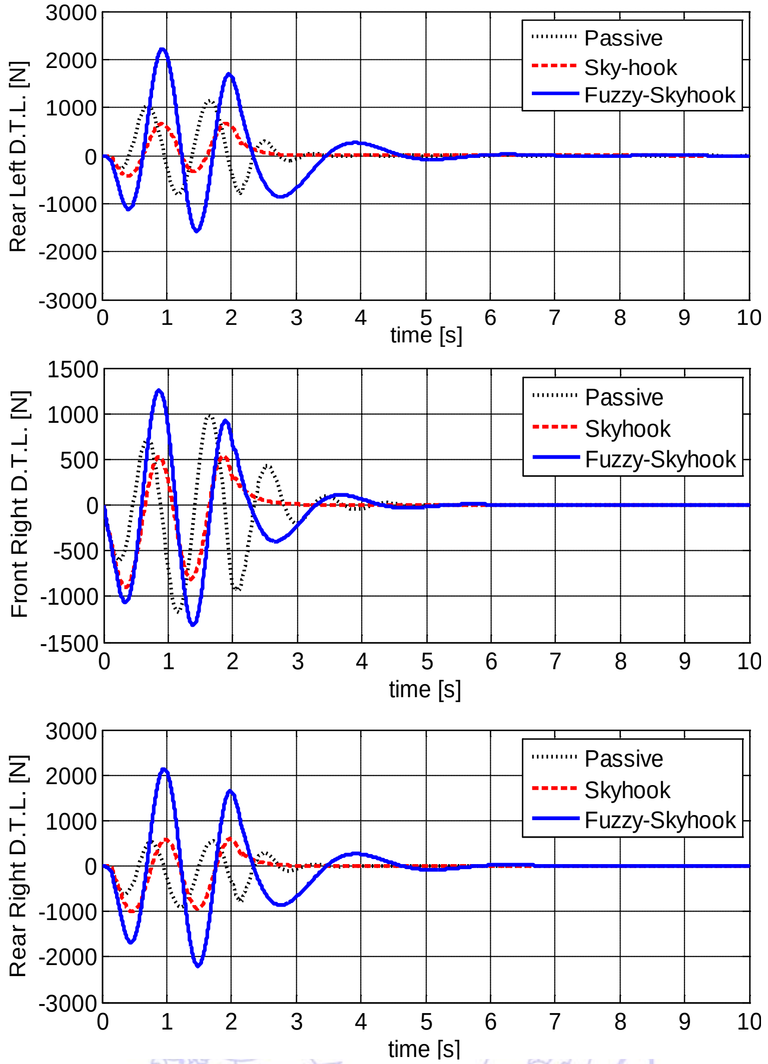

Fig. 8 Comparison between the passive, skyhook and active fuzzy-skyhook suspension systems in terms of dynamic tyre load at each corner

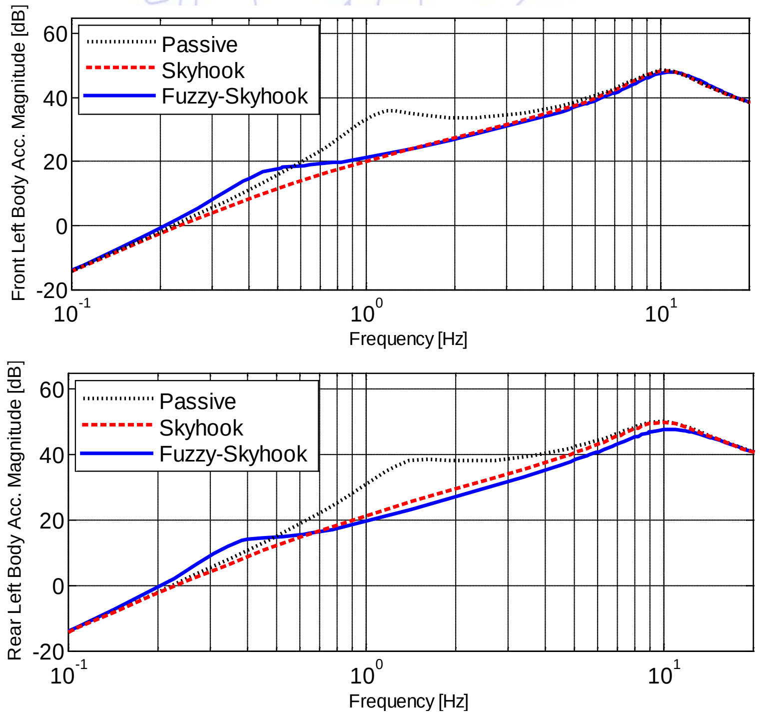

Fig. 9 Comparison between the passive, skyhook and active fuzzy-skyhook suspension systems in terms of body acceleration at each corner (continued)

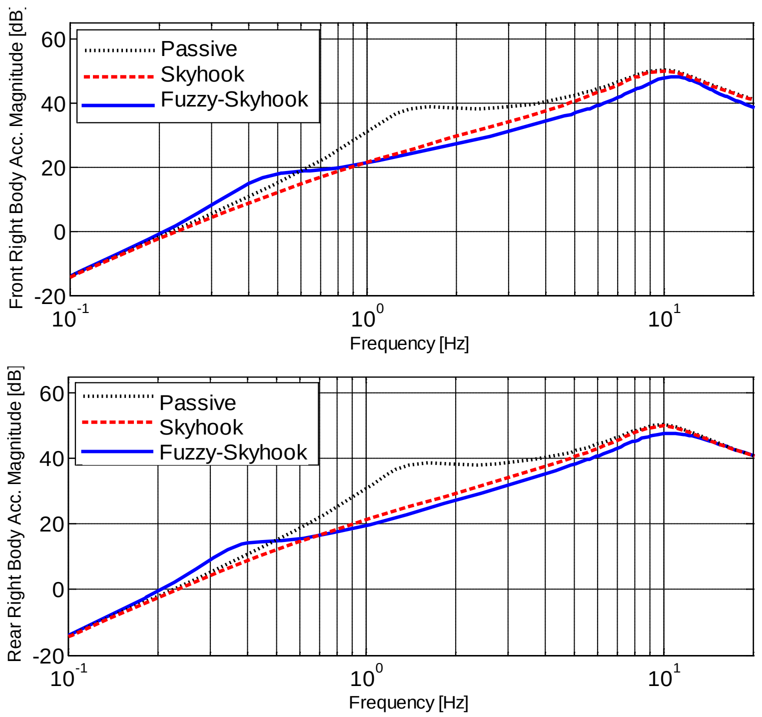

Fig. 9 Comparison between the passive, skyhook and active fuzzy-skyhook suspension systems in terms of body acceleration at each corner

Fig. 9 shows a comparison between body acceleration of the passive, skyhook and active fuzzy-skyhook suspension systems at each corner in frequency domain. The improvement in ride comfort is clearly seen around body resonance peak around 1 Hz and 10 Hz for all accelerations.

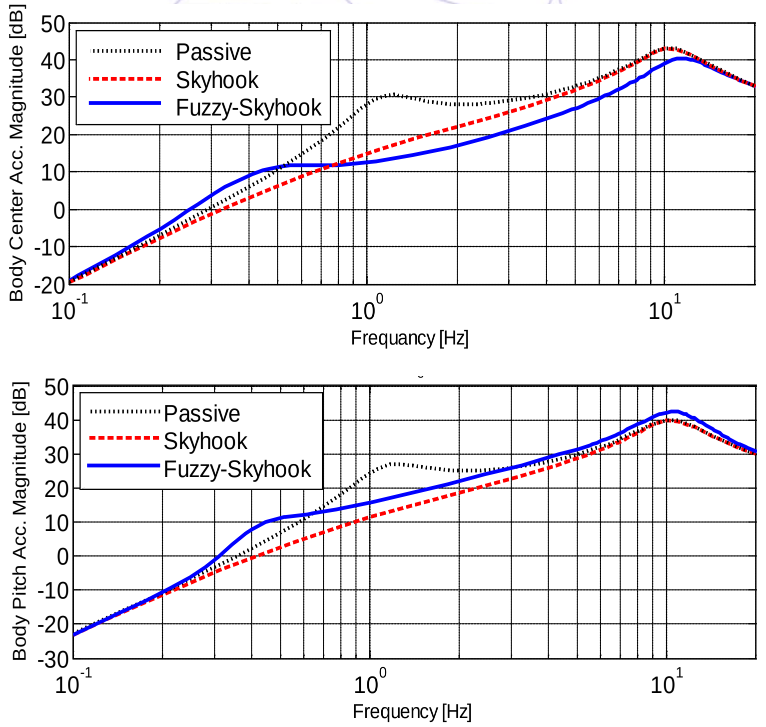

Fig. 10 Comparison between the passive, skyhook and active fuzzy-skyhook suspension systems in terms of the body center, pitch and roll acceleration(continued)

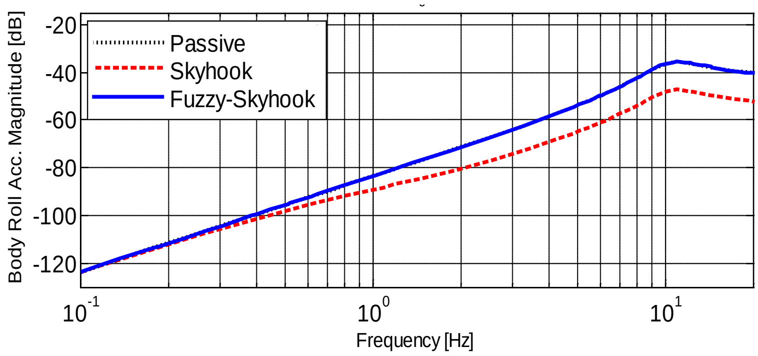

Fig. 10 Comparison between the passive, skyhook and active fuzzy-skyhook suspension systems in terms of the body center, pitch and roll acceleration

Fig. 10 shows a comparison between the passive, skyhook and active fuzzy-skyhook suspension systems for the body centre, pitch and roll accelerations. An improvement in the body center acceleration occurs in the body and wheel resonance, while the improvement in pitch acceleration is obtained at the body resonance only. However, improvement in roll acceleration cannot occur because it's very small.

Table 2 summarizes the results for the passive, skyhook and active fuzzy-skyhook suspension systems. The suggested fuzzy-skyhook active suspension system offers a significant improvement in the RMS of the body accelerations compared with the passive system. However, these improvements are obtained at the expense of increased suspension working space and dynamic tyre load.

Table 2 R.M.S. values of the ride comfort performance criteria for passive, skyhook and active fuzzy-skyhook suspension systems.

Parameter	**Passive**	**Skyhook**	**Fuzzy-Skyhook**
Front L. Acc [m/s^2]	0.7286	0.2002	0.2413
Rear L. Acc [m/s^2]	0.8288	0.2316	0.3792
Front R. Acc [m/s^2]	0.8420	0.2002	0.2511
Rear R. Acc [m/s^2]	0.9652	0.2316	0.3870
B.Center Acc [m/s^2]	0.7612	0.1997	0.2438
B.Pitch Acc [rad/s^2]	0.1395	0.05816	0.1370
Front L. S.W.S [m]	0.01540	0.007718	0.00882
Rear L. S.W.S [m]	0.01417	0.003650	0.004733
Front R. S.W.S [m]	0.013800	0.011580	0.011330
Rear R. S.W.S [m]	0.007581	0.010280	0.015040
Front L. D.T.L [N]	353.3	162.0	324.7
Rear L. D.T.L [N]	301.6	181.9	599.7
Front R. D.T.L [N]	321.8	238.0	387.0
Rear R. D.T.L [N]	266.3	233.7	600.4

7. Conclusions

A new Fuzzy-skyhook controller of an active suspension system has been presented. The proposed active suspension system controller uses the body vertical, pitch and roll accelerations signals, and the determined error in these signals in comparison with the ideal skyhook signals as a controller input signals. The actuator desired force at each wheel corner is generated by the controller. The performance of the proposed controller is evaluated via computer simulation. The proposed controller gives a significant improvement in ride comfort parameters in assessed time domain; also, it provides adequate performance at the body resonance in the frequency domain and improves the vehicle ride performance compared with the passive suspension.

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