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Fuzzy rules incorporated skyhook theory based vehicular suspension design for improving ride comfort

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Abstract
The vehicle suspension system supports and isolate the vehicle body and payload from road vibrations due to surface roughness by maintaining a controllable damping traction force between tires and road surface. In modern luxury vehicles semi active suspension system are offering both the reliability and accuracy that has enhanced the passenger ride comfort with less power demand. In this paper we have proposed the design of a hybrid control system having a combination of skyhook theory with fuzzy logic control and applied on a semi-active vehicle suspension system for its ride comfort enhancement. A two degree of freedom dynamic model is simulated using Matlab/Simulink for a vehicle equipped with semi-active suspension system with focused on the passenger's ride comfort performance.
Keywords-- Skyhook Theory, Ride comfort, suspension system, Fuzzy logic control, 2-Degree of freedom vehicle model.

I. Introduction

The ride comfort is one of the most important characteristics for a vehicle suspension system. By reducing the vibration transmission and keeping proper tire contacts, the active and semi-active suspension system are designed and developed to achieve better ride comfort performance than the passive suspension system. The active suspension is designed to use separate actuators which can exert an independent force on the suspension, this action is to improve the suspension ride comfort performance [1,2].

Suspension system is one of the important components of a vehicle, which plays a crucial role in handling the performance and ride comfort characteristics of a vehicle. A suspension system acts as a bridge between the occupants of a vehicle and the road on which it rides. It has two main functionalities. One is to isolate the vehicle body with its passengers from external disturbance inputs, which mainly come from irregular road surfaces. It always relates to riding quality. The other is to maintain a firm contact between the road and the tires to provide guidance along the track. This is called handling performance.

In a conventional passive suspension system, which is composed of only springs and dampers, a trade off is needed to resolve the conflicting requirements of ride comfort and good handling performance[3]. The reason is that stiff suspension is required to support the weight of the vehicle and to follow the track; on the other hand, soft suspension is needed to isolate the disturbance from the road. Hence, there exists a significantly growing interest in the design and control of active suspension systems for automotive engineers and researchers over the past three decades. An active suspension system is characterized by employing certain kinds of suspension force generation, such as pneumatic, magneto-rheological, or hydraulic actuators. Practical applications of active suspension systems have been facilitated by the development of microprocessors and electronics since the middle 1980s [3,4].

The active suspension system has been investigated since 1930s, but for the bottle neck of complex and high cost for its hardware, it has been hard for a wide practical usage and it is only available on premium luxury vehicle. Semi-active (SA) suspension system was introduced in the early 1970s, it has been considered as good alternative between active and passive suspension system. The conceptual idea of SA suspension is to replace active force[5] actuators with continually adjustable elements, which can vary or shift the rate of the energy dissipation in response to instantaneous condition of motion.

In this paper we have proposed the design of a hybrid control system, combination of skyhook surface sliding mode control method and fuzzy logic control method and applied on a semi-active vehicle suspension system for its ride comfort enhancement. A two degree of freedom dynamic model of a vehicle semi-active suspension system[6] is given which focused on the passenger's ride comfort performance. The design and simulations are performed on MATLAB/SIMULINK software.

II. Related Work

An active suspension control of a vehicle model was designed [2] that has five degrees of freedom with a passenger seat using a fuzzy logic controller is studied. Three cases are taken into account as different control applications. In the first case, the vehicle model having passive suspensions with an active passenger seat , active suspensions with passive passenger seat combination are controlled and both the passenger seat and suspensions have active controllers. Vibrations of the passenger seat in the three cases due to road bump input are simulated. At the end of the study, the results are compared in order to select the combination that supplies the best ride comfort.

Jiangtao Cao et. al., (2008) [3] gave review of computational-intelligence involved methods in active vehicle suspension control systems with a focus on the problems raised in practical implementations by their nonlinear and uncertain properties. After a brief introduction on active suspension models, the work explores the state of the art in fuzzy inference systems, neural networks, genetic algorithms, and their combination for suspension control issues. Chen, (2009) [5] gave a skyhook surface sliding mode control method to control the semi-active vehicle suspension system for its ride comfort enhancement. A two degree of freedom dynamic model of a vehicle semi-active suspension system was given, which focused on the passenger's ride comfort performance.

Recently Particle Swarm Optimization (PSO) technique is applied [1] to tune the Adaptive Neuro Fuzzy Controller (ANFIS) for vehicle suspension system. LQR controller is used to obtain the training data set for the vehicle suspension system. Subtractive clustering technique is used to formulate ANFIS which approximates the actuator output force as a function of system states. PSO algorithm search for optimal radii for subtractive clustering based ANFIS. Training is done off line and the cost function is based on the minimization of the error between actual and approximated output. Simulation results show that the PSO-ANFIS based vehicle suspension system exhibits an improved ride comfort and good road holding ability.

M. Kondalu et. al. [4] designed a fuzzy logic based control systems which provide a simple and efficient method to control highly complex and imprecise systems. However, the lack of a simple hardware design that is capable of modifying the fuzzy controller's parameters to adapt for any changes in the operation environment, or behaviour of the plant system limits the applicability of fuzzy based control systems in the automotive and industrial environments. Adaptive control is the control method used by a controller which must adapt to a controlled system with parameters which vary or are initially uncertain. Despite the lack of a formal definition, an adaptive controller has a distinct architecture, consisting of two loops control loop and a parameter adjustment loop.

III. Methodology

A. Two Degree of Freedom Semi-Active Suspension System:

A two degree of freedom model which focused on the passenger ride comfort performance is proposed for SA suspension system in Figure 1. The SA suspension model can be defined by the Equation (1), where, m1 and m2 are the un-sprung mass and the sprung mass respectively, k1 is tire deflection stiffness, k2 and c2 are suspension stiffness and damping coefficients respectively, ce is the semi-active damping coefficient which can generate damping force of f_d by MR/ER absorber in Equation (2). z1, z2 and q are the displacements for un-sprung mass, sprung mass and road disturbance respectively, g is the acceleration of gravity.

$$\mathbf{m_1 z_1'' + k_2 (z_2 - z_1) + (c_2 + c_e)(z_2' - z_1') - k_1(z_1 - q) + m_1 g} \quad (1)$$

$$\boldsymbol{m_2 z_2'' - k_2 (z_2 - z_1) - (c_2 + c_e)(z_2' - z_1') + m_2 g = 0} \quad (2)$$

Then let's say $\mathbf{f_d = c_e(z_2' - z_1')}$.

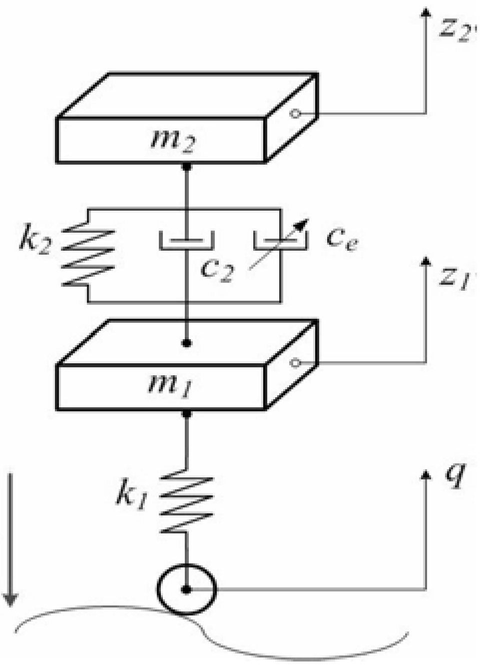

Figure 1: Two degree of freedom semi-active suspension system.

The objective is the design of non-linear tether system as the controlled plant, and therefore defined by the general equation s(e,t) is the sliding surface of the hyper-plane, which is given in Equation (3) and shown in Figure 2, where λ is a positive constant that defines the slope of the sliding surface. In the 2-DOF SA suspension system, we let n = 2, given that, as it is a second-order system in which s de-fines the position and velocity errors.

$$s = e' + \lambda e \quad (3)$$

From Equations (3), the second-order tracking problem[8] is replaced by a first-order stabilization problem in which the scalar s is kept at zero by means of a governing condition obtained from use of the Lyapunov stability theorem, given in Equation (4) having the origin as a globally asymptotically stable equilibrium point for the control system. Equation (4) is positive definite and its time derivative is given in inequality (5):

$$V(s) = 1/2\, s^2 \quad (4)$$

$$V(\dot{s}) = s\dot{s} < 0 \quad (5)$$

Figure 3 gives the ideal skyhook control scheme, the basic idea is to link the vehicle body sprung mass to the stationary sky by a controllable 'skyhook' damper, which could generate the controllable force of skyhook and reduce the vertical vibrations by the road disturbance of all kinds. In practical, the skyhook control law was designed to modulate the damping force by a passive device to approximate the force that would be generated by a damper fixed to an inertial reference as the 'sky'.

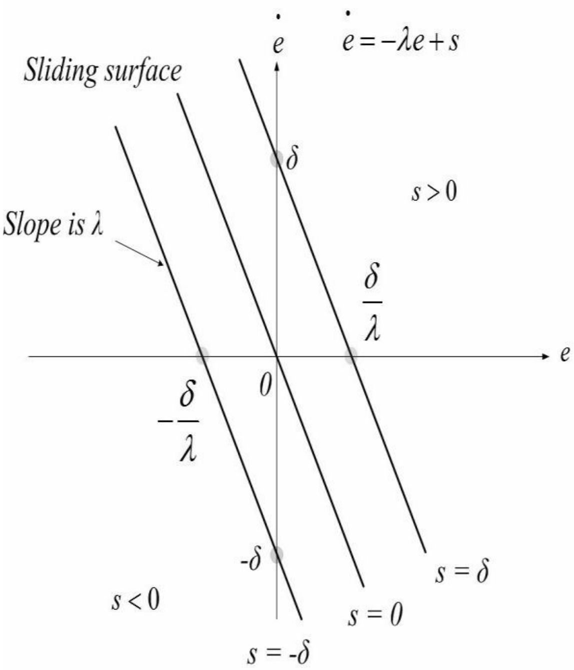

Figure 2: Sliding surface design.

The skyhook control can reduce the resonant peak of the sprung mass quite significantly and thus can achieve a good ride quality. By borrowing this idea [9,10] to reduce the sliding chattering phenomenon, in Figure 4, a soft switching control law is introduced for the major sliding surface switching activity in Equation (6), which is to achieve good switch quality for the Skyhook SMC. The variable of s is defined in Equation (3), which contains the system information. It can be taken as a part of the Skyhook SMC control law in Equation (6), where c0 is an assumed positive damping ratio for the switching control law. Noting that δ is an assumed positive constant which defines the thickness of the sliding mode boundary layer [4].

$$u_{sky\,hook} = \begin{cases} -c_o \tanh\left(\frac{s}{\delta}\right) & s\dot{s} > 0 \\ 0 & s\dot{s} \le 0 \end{cases} \quad (6)$$

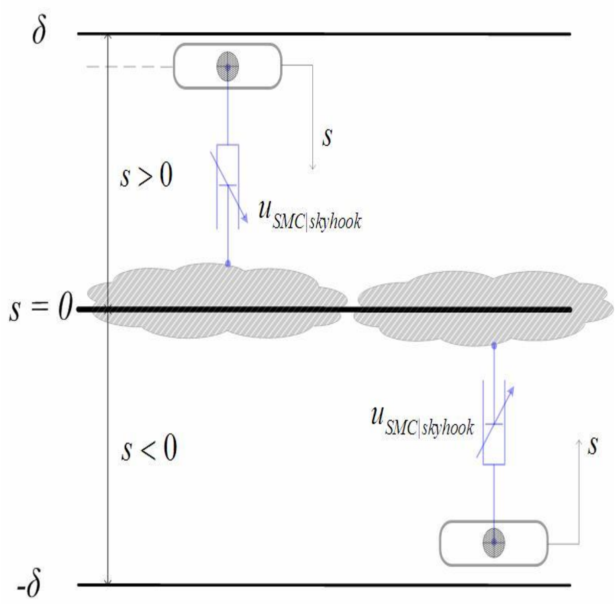

Figure 3: Sliding mode surface design with skyhook control law.

B. Model Generation Of Road Disturbance:

This model (figure 4) consists of two signals representing the body vibrations in terms of rate of change of vertical displacement.

We have used a manual switch which can pass anyone of the road disturbance vibration to the integrator block. The integration in this way receives body vibration i.e. dq/dt and returns q as its output i.e. vertical displacement of the suspension system occurring at the tire and road point of contact.

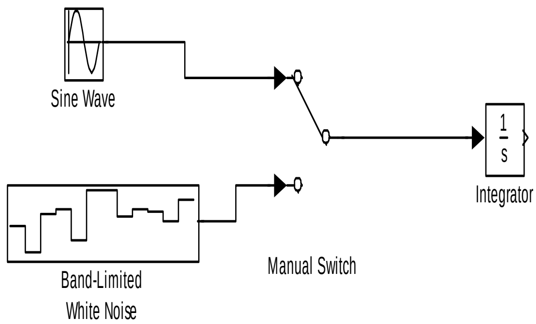

Figure 4: Model Generation of Road Disturbance

C. Model Of Force Balance Equation For Un-Sprung Mass

In this model we have connected these road disturbance signals to force balance equation (1) of un-sprung mass (m1). This equation uses parameters given in table: (1).This model represents force equation for un-sprung mass.

This figure consists of data input blocks representing the simulation parameters used in the force equation of 2-DOF SAS system.

The unmasked diagram of data input block it consists of & constant input blocks in which we have defined the parametric values of m1,m2,k1,k2, co, fr, g .all the constant input pass through a multiple block of size 7x1 as the mux output is mentioned as simulation parameter. The multiplexed output is then de-multiplexed using a de-multiplexer and we are considering mass m1 along with displacement z1 and z2 obtained from the output of the product block. In this model summer bock is producing m1z1" as the force produced on acting on un-sprung mass m1 where z1" is the acceleration of m1 due to body inertia & load disturbance. This force is summation 0f k1(z1-q), k2(z1-z2), c0(z1'-z2'), -m1g and fr (=c2(z2'-z1')) and the output of sum up is multiplied by 1/m1 using product block. In this way the product block is providing z1"

Table 1: 2-DOF SA suspension parameters

m1	Un-sprung mass, kg	36
m2	Sprung mass	240
c2	Suspension damping coefficient, Ns/m	1400
k1	Tire stiffness coefficient, N/m	160000
k2	Suspension stiffness coefficient, N/m	16000
G	Gravity acceleration, m/s^2	9.81
Ke	FLC scaling gain for e	-1
Kec	FLC scaling gain for ec	-10
Ku	FLC scaling gains for u	21
Co	Skyhook SMC damping coefficient	-5000
Δ	Thickness of the sliding surface	28.1569
Λ	Slope of the sliding surface	10.6341
No	Reference space frequency ,m^{-1}	0.1
P(no)	Road roughness coefficient, m^3/cycle	$250x10^{-6}$
Vo	Velocity, km/h	72

Now similarly we connect these road disturbance signals to force balance equation (2) of sprung mass (m2). This equation uses parameters given in table: (1).This combined model represents force equation for un-sprung mass and sprung mass. The multiplexed output is then de-multiplexed using a de-multiplexer and we are considering mass m1 along with displacement z1 and z2 obtained from the output of the product block. In this model summer bock is producing m2z2" as the force produced on acting on sprung mass m2 where z2" is the acceleration of m1 due to body inertia.

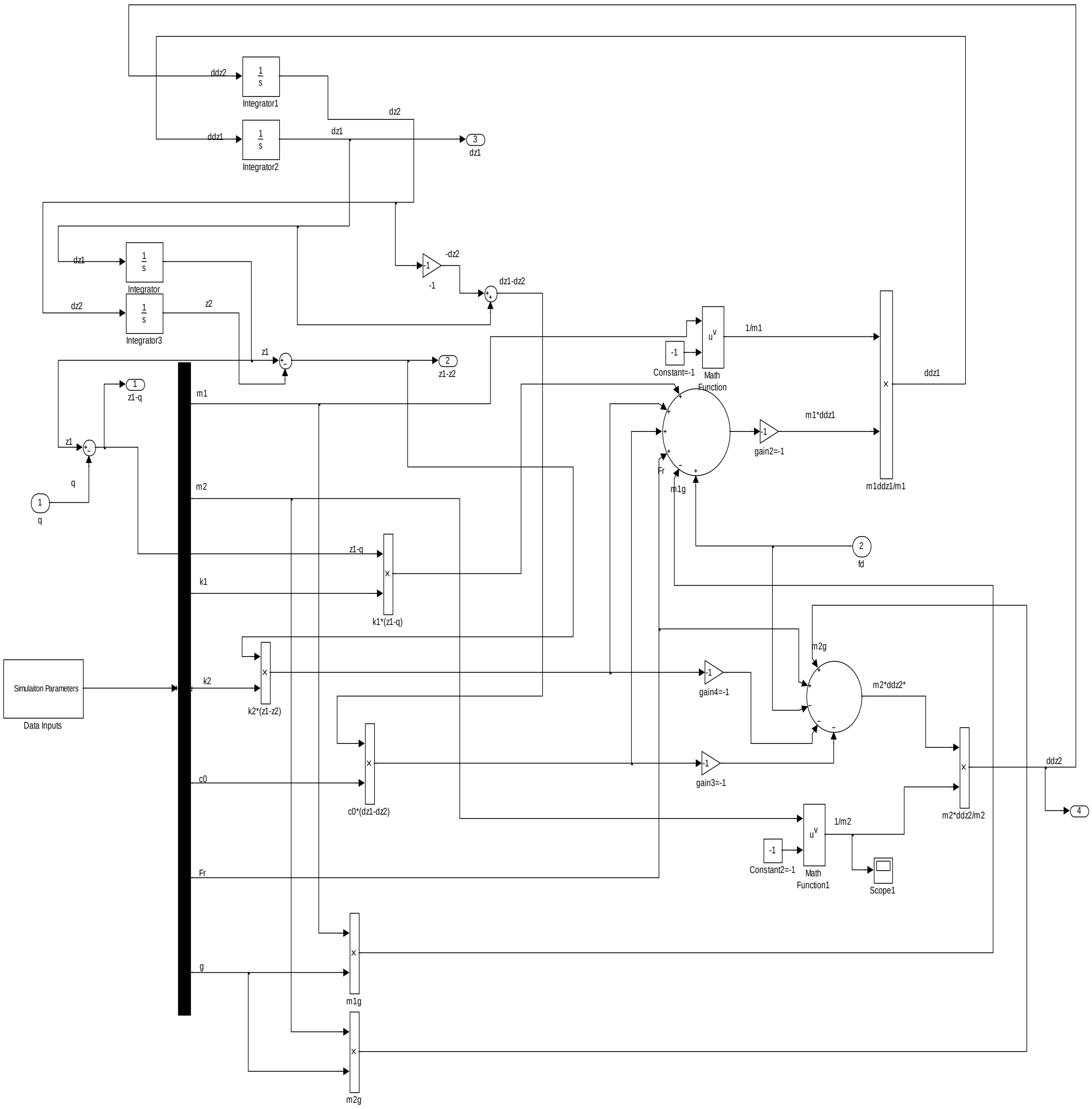

Figure 5: Combined Model of Force Balance Equation for Un-sprung & Sprung Mass

IV. Result and Discussion

We have designed a 2DOF suspension system having semi-active suspension vehicle. The model is designed in MATLAB/SIMULINK having two type of controllers-Fuzzy and Skyhook SMC. We have designed also a passive suspension system for comparing our results in terms of body acceleration, tire load, suspension distortion.

For this purpose 4 different cases are considered for generating our simulation results. All of the 4 cases are described below-

CASE 1 PASSIVE

In this case we have considered a passive suspension system without any application of suspension controllers.

CASE 2 FUZZY

This case involves a closed loop fuzzy controller for minimizing body acceleration by varying parameters of suspension system of 2DOF model. The inputs to this fuzzy controller are error (e) and change in error (ec) and output is taken as semi-active control force (u).

CASE 3 SKYHOOK

In this case skyhook SMC are used to provide a better body acceleration, tire stiffness and suspension distortion. This controller has 3 input as z, z' and z" where they are named as e, ec, ecc where z represents the displacement of body due to road surface distortion.

e- velocity

ec- acceleration

ecc- change in acceleration

CASE 4 HYBRID

This is the case when both fuzzy and skyhook control force are combined to generate a controlling force F-fuzzy and F-skyhook controller (Skyhook SMC) forces then

$$F=\alpha.fd(fuzzy)+(1-\alpha)fd(skyhook)$$

Where α =0.5

Table 2: Initial Range

	Body Acc. (m/sec^2)	Tire Stiffness (m/sec^2)	Suspension Distortion (m)
Passive	10.64 to 5.762	4321 to 1633	-0.02 to -0.1363
Fuzzy	9.498 to -5.69	4570 to 1616	-0.2246 to -0.1511
Skyhook	9.627 to -5.1	3870 to 1931	-0.186 to -0.1607
Hybrid	9.363 to -4.278	4264 to 2181	-0.2063 to -0.1596

Table 3: Steady State Range

	Body Acc. (m/sec^2)	Tire Stiffness (m/sec^2)	Suspension Distortion (m)
Passive	-2 to +2	3404 to 2205	-0.152 to -0.18
Fuzzy	-2 to +2	3331 to 2094	-0.17 to -0.16
Skyhook	-1.3 to +1.3	3398 to 1953	-0.18 to -0.16
Hybrid	-1.15 to +1.13	3527 to 2125	-0.17 to -0.16

All the above shown figures are again collectively shown in fig 6 to fig 7. The results are also demonstrated in the form of table 2 and table 3 as the range of different responses during initial stages and the steady state stage. Fig 8 is obtained by taking the Fourier transform of the body acceleration/ road displacement versus the frequency in hertz. Since human body is mainly sensitive to accelerations in the frequency range of max 10 hertz hence fig 4.17 is again shown in the enlarged view to observe the reduction in body acceleration by all the four method. In this fig we can clearly see that our proposed hybrid controller gives minimum resonance peak of the acceleration.

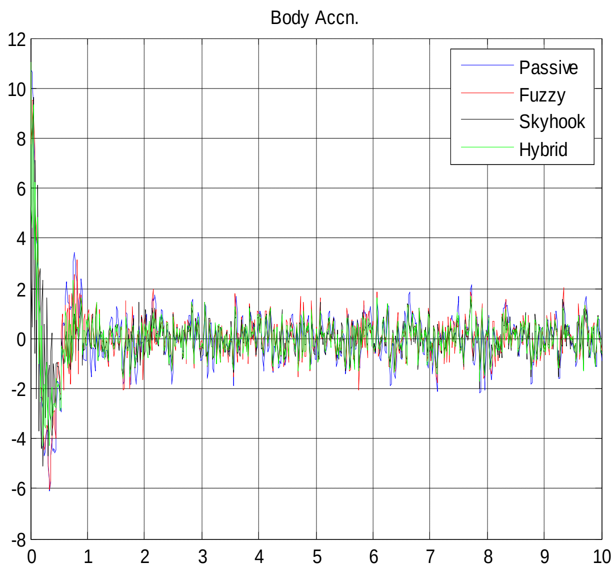

Fig 6: Combined Plot of Body Acc.

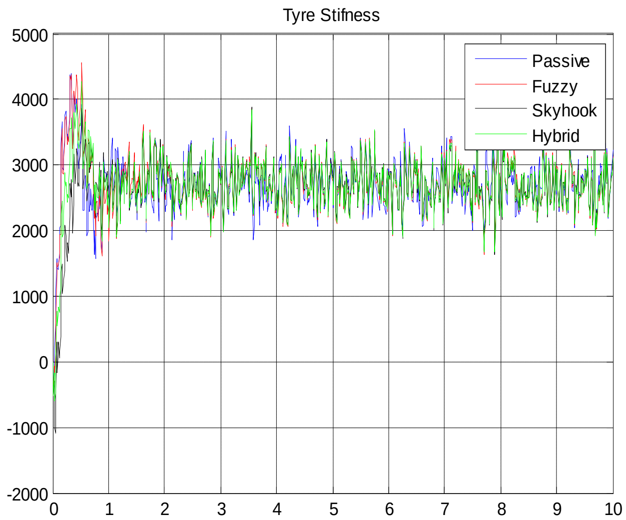

Fig 7: Combined Plot of Tire Stiffness.

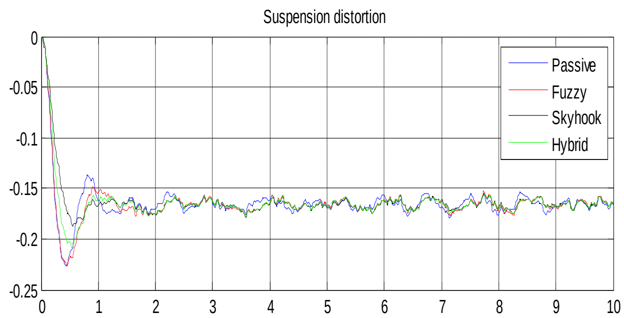

Fig 8: Combined Plot of Suspension Distortion.

V. Conclusion

We have developed 4 simulated models for analyzing the performance results of 2 Degree of freedom based semi active vehicle suspension system for improving the ride comfort of the passenger. The measures which are considered to justify the design performance are body acceleration, tyre deformation and suspension distortion values due to road disturbances. In the initial and steady states both the hybrid fuzzy skyhook control mechanism gave the lowest body acceleration compared to the other three suspension control; mechanism. Similarly for the case of tyre stiffness and suspension distortion both fuzzy and hybrid system are giving near about equally best performance during the steady state. In this way we can conclude that the combined effect of fuzzy and skyhook control strategies has provided significant improvement in ride comfort by damping the vibration forces.

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