DEVELOPMENT OF A SEMI-ACTIVE CAR SUSPENSION CONTROL SYSTEM USING MAGNETO-RHEOLOGICAL DAMPER MODEL.

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ABSTRACT

In this paper, the development of a semi- active suspension control of quarter car model using fuzzy-based controller has been done. The quarter car model to be used here can be described as a nonlinear two degrees of freedom system which is subject to excitation from different road profile. The semi-active control is designed as the fuzzy control inferred by using two single input rule fuzzy modules, and the road model is used as the control force is released by actuating an electromagnetic shaker. To implement semi-active suspension system experimentally, the MR damper is used here as the adjustable damper. The MR damper is a control device that consists of a hydraulic cylinder filled with magnetically polarizable particles suspended in a liquid. MR dampers dissipate vibration by absorbing energy. Magnetorheological (MR) fluids dampers are very effective to control vibration, which use MR fluids to produce controllable damping force and provide both the reliability of passive systems and the facility of active control systems with small power supply. Due to their mechanical simplicity, high dynamic range, low power requirements, large force capacity, and robustness, offer an attractive means of vibration protection. The objectives of this are modeling of semi-active suspension system, developing controller and understanding the characteristics of the MR damper to provide effective damping for the purpose of suspension isolation or suppression car model. In this work pid, fuzzy logic and fuzzy-hybrid controller are used to control semi-active car suspension system.

Keywords: Quarter car model, Semi-active suspension system, fuzzy logic controllers, Semiactive, Suspension, MR Damper, Fuzzy Controller

1 INTRODUCTION

A semi-active suspension (Giua, 1999, Kitching, 2000, Roberti 1993) consists of a spring and a damper but, unlike a passive suspension, the value of the damper coefficient can be controlled and updated.

Semi-active dampers change their damping force in real time according to a controller policy, which is usually based on the system dynamics. Simply adjusting the damper's resistance to motion, or damping coefficient, changes the damper force. The ability to vary the semi-active damping coefficient independently of damper velocity, within limits, has prompted a number of individuals and companies to explore the possibility of improving suspension performance by using semi-active damper technology. As noted by Pare (Ahmedian, 2000), most research concludes that, at least in certain aspects, semi-active dampers are modification of the passive damper.

To implement the semi-active control law, the semi-active damper must be adjustable in real time. Currently, semi-active dampers can be adjusted hydraulically or electromagnetically. The first category uses mechanical valves driven by a solenoid or stepper motor to control damper force in a hydraulic damper. In the latter category, the rheological effect of controllable fluids, such as magneto rheological or electro rheological fluid, is used to provide adjustable damping forces. Although mechanical control dampers have been researched and developed extensively, the rheological controllable dampers have only received much more attention in the past few years, mainly due to great advances in magneto rheological fluids.

Semi-active dampers are potentially a very attractive method of controlling suspension in order to improve its performance. One semi-active device that appears to be particularly promising for suspension protection is the MR damper. MR dampers use MR fluids to produce controllable dampers. Lazareva *et al.* (1997) studied the properties of MR fluids that are based on barium and strontium ferrites and iron oxides. The fluids were prepared using various combinations of the materials, and their properties, such as the MR effect, were studied. Ashour *et al.* studied the effects of components of the MR on sedimentation of the magnetic particles and initial viscosity. In another study, Ashour *et al. (*1996) studied the general composition of MR fluid along with the methods that are used to evaluate the performance of the fluids. Carlson *et al.* [1999] studied the advantages of MR

over ER fluid devices in areas such as the yield strength, the required working volume of fluid, and the required power. The operational modes of the MR fluid are presented along with the linear fluid damper, the rotary brake, and the vibration damper. Kordonsky (1996) developed the concept of the MR converter (or valve) and applies the MR converter to create devices such as the MR linear damper, the MR actuator, and the MR seal. Finally Bolter *et al.* (1997) examined the rules that should be applied when designing the magnetic circuit for MR devices that are working in the different modes of the MR fluid. Bolter also examined the use of permanent magnets in the design of the magnetic circuit to change the operational point of the MR device. When a magnetic field is applied to the fluid, particle chains form, and the fluid becomes a semi-solid and exhibits viscoplastic behaviour similar to that of ER fluid. This controllable change of state with some desirable features such as high strength, good stability, broad operational temperature range and fast response time gives rise to isolation and suspension system applications. MR fluid dampers considered here are semi-active control devices that use MR fluids to produce controllable damping forces.

The main objectives of this paper is to develop fuzzy based controllers for semi-active suspension control and to the utilize ability of the MR damper to eliminate and reduce suspension over a wide range. The results reported herein indicate that this semi-active control system is quite effective for suspension control.

2. Semi active Car suspension systems

A semi active damper suspension system varies the damping force in real time depending on the dynamics of the controlled masses. The effect of suspension performance has also been studied on a two degree of freedom (two mass) system, such as the one depicted in Fig.1. This model is the quarter car model using (one of four wheels) which is used to simplify the problem to a one-dimensional spring-damper system

The motion equations of the car body and the wheel are as follows:

$$m1\ddot{y} = -k1(y - x) - \tilde{b}1(\dot{y} - \dot{x}) \qquad (1)$$

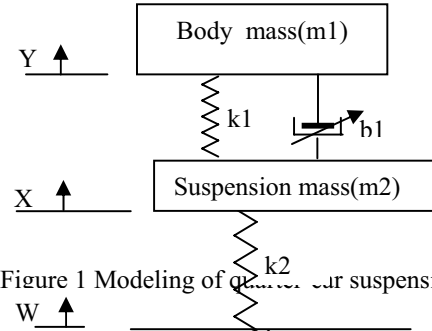$$m2\ddot{x} = k1(y - x) - k2(\dot{x} - \dot{w}) \qquad (2)$$

Figure 1 Modeling of quarter car suspension system

Suspension parameters used in quarter-car model are as follows.

Parameter	Value
Sprung Mass (m1)	325 kg
Unsprung Mass (m2)	55 kg
Suspension Stiffness (k1)	42,000 N/m
Tire Stiffness (k2)	180,000 N/m

The damper coefficient of MR damper ($\tilde{b}1$) which is controlled variable.
The Bouc-Wen model is the suitable mathematical presentation of the MR Damper. In Equation 1 and 2, the basic semi active model is presented and $\tilde{b}_1$ is variable damping value of MR damper. For application of MR damper in suspension control, the model of the MR damper should be continuous in all the ranges and be numerically tractable, and the Bouc–Wen model is adopted here as shown in Figure.2.
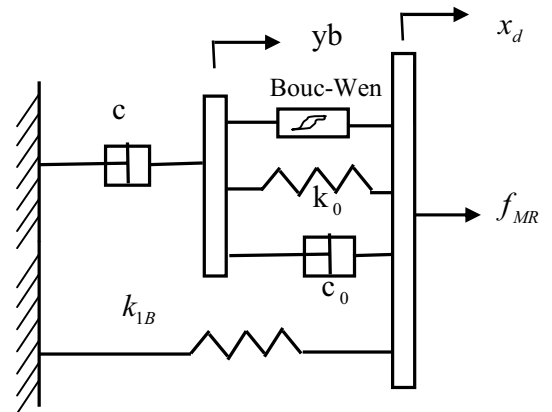

Figure 2   Mechanical model of the MR damper.

The force in this system is given by f_{MR} predicted by this model as

$$f_{MR} = c_1\dot{y}_b + k_{1B}(x_d - x_0) \qquad (3)$$

$$\dot{z} = -\gamma |\dot{x}_d - \dot{y}_b| z |z|^{n-1} - \beta(\dot{x}_d - \dot{y}_b)|z|^n + A(\dot{x}_d - \dot{y}_b)....(4)$$

$$\dot{y}_b = \frac{1}{c_0 + c_1}\{\alpha z + c_0 \dot{x}_d + k_0(x_d - y_b)\}...(5)$$

where z is an evolutionary variable that accounts for the history dependence of the response. The model parameters depend on the voltage v to the current driver as follows

$$\alpha = \alpha_a + \alpha_b u, \ c_1 = c_{1a} + c_{1b}u,$$

$$c_0 = c_{0a} + c_{0b}u...(6)$$

where u is given as the output of first-order filter as follows

$$\dot{u} = -\eta(u - v)..(7)$$

The filter is used after the MR damper output, which can be seen in the later section. Equation 6 is necessary to model the dynamics involved in reaching rheological equilibrium and in driving the electromagnet in the MR damper. There are a total of 14 parameters c_{0a}, c_{0b}, k_0,

$,c_{1a}, c_{1b}, k_{1B}, \ x_0, \ c_{0a} \ c_{0b}, \ k_0, \ c_{1b}, c_{1a}, \ \ x_0$ characterizing the MR damper and values of all parameters are shown in Table 1. All the values of parameters in the Table 1 are use in the simulation and fuzzy control of the MR damper model.

The MR Damper can be modeled in such way in where the damper force depends on the coil current directly. The simulation work have been done here on this model because current is the direct driving parameter for the MR Damper in the real world.

Table 1 Parameter values for MR damper (Spencer 1997)
In order to calculate and reproduce the force of the damper, the mechanical model of the MR damper proposed by Spencer et al. (1997) is utilized. Equations 8, 9 and 10 are used to show the relation between current and other parameters of the MR damper;

Parameter	Value	Para-meter	Value
c_{0a}	784 N s m−1	α_a	12 441 N m−1
c_{0b}	1803 N s V^{-1} m^{-1}	α_b	38 430 N V−1m−1
k_0	37810 N/m	γ	136 320 m−2
c_{1a}	14649 N s m^{-1}	μ	2059 020 m−2
c_{1b}	34622 N s V−1 m−1	A	2679 m^{-1}

$$\alpha(i) = 1646i^3 - 8701i^2 + 1626i + 1514 \ ... . (8)$$

$$c_0(i) = 4377i^3 - 1507i^2 + 1676i + 4741.......(9)$$

$$c_1(i) = -9308i^3 + 5383i^2 + 4840i - 2730 .....(10)$$

where y_b is the internal displacement of the MR damper, x_b is the damper displacement in the x-direction, i is the current of damper coil and the additional variables are constants with the following values: x_o =0.18 m, k_{1B} =617.31 N/m, β=647.46 m^{-1}, n=10 (Yang et al. 2001).

Equations 3, 4, 5, 6, 7, 8, 9 and 10 were modeled using the Matlab/Simulink toolbox. The input for this model is current and the output is the MR damper force. Simulation of this model have been done using different input currents (1, 0.8, 0.6, 0.4, 0.2, 0, -0.8 and -1.0 amp) and response of the MR model to these current inputs is shown in Figure.3. The dynamic response of the MR damper used to control the semi active suspension will be discussed in the following sections.
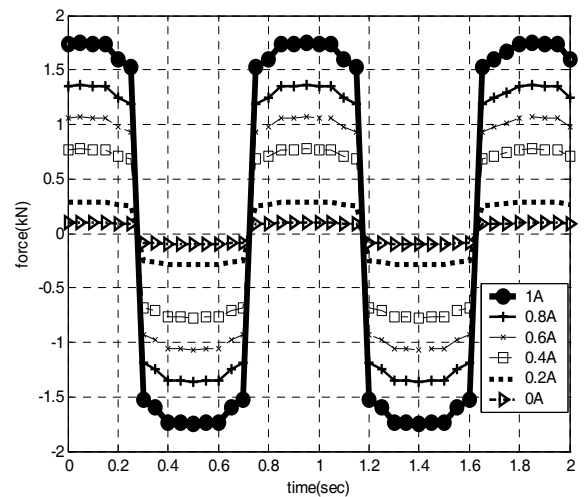

Figure 3 MR damper force characteristics curve with variable current.

From these dynamic responses of the MR damper, it can be seen that the output force of MR damper varies regularly for currents of positive values. But for currents of negative values the change of forces is not regular. So when the MR model is used to control the suspension, the control current value has to be kept within positive values by the controller action.

4. The control scheme:

The MR model described in the Figure 4 has been combined with quarter car system (semi active model) and the combined model has been shown in Figure 5. In this

semiactive model fuzzy logic and Fuzzy-hybrid control strategy were used together. Here sprung mass velocity $\dot{x}$ and difference between sprung mass velocity and unsprung mass velocity $(\dot{y} - \dot{x})$ were used as fuzzy inputs. Fuzzy output was feed to the MR damper as input and then the output from MR damper is feed to suspension system.
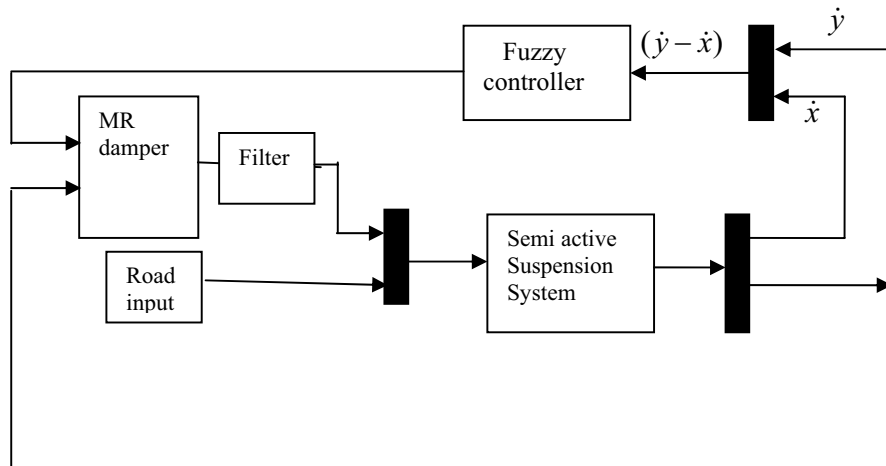

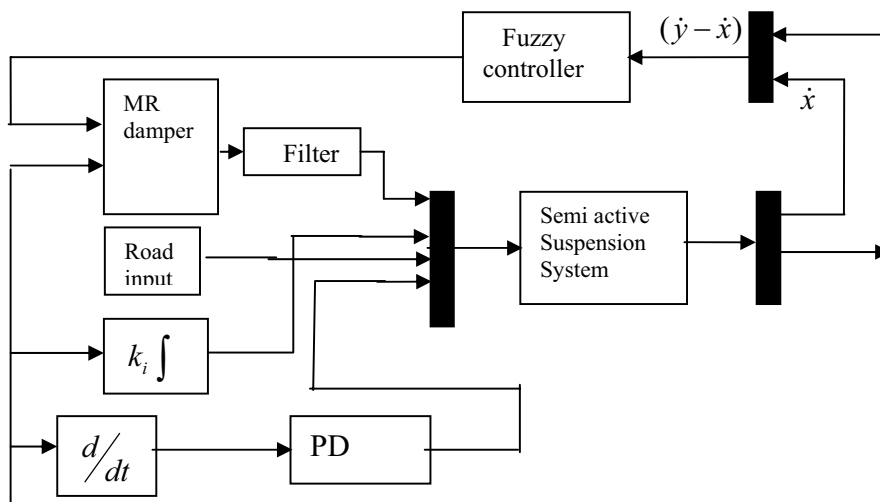Figure 4 Semi active suspension control model with MR Damper using fuzzy logic

Figure 5 Semi active suspension control model with MR Damper using fuzzy hybrid controller

The Mamdani type Fuzzy (FIS) structure was developed for the fuzzy logic rules and there were 49 triangular rules similar to that used in the active suspension system.

The filter is used here to block undesired noise from the MR damper to the semi-active suspension.
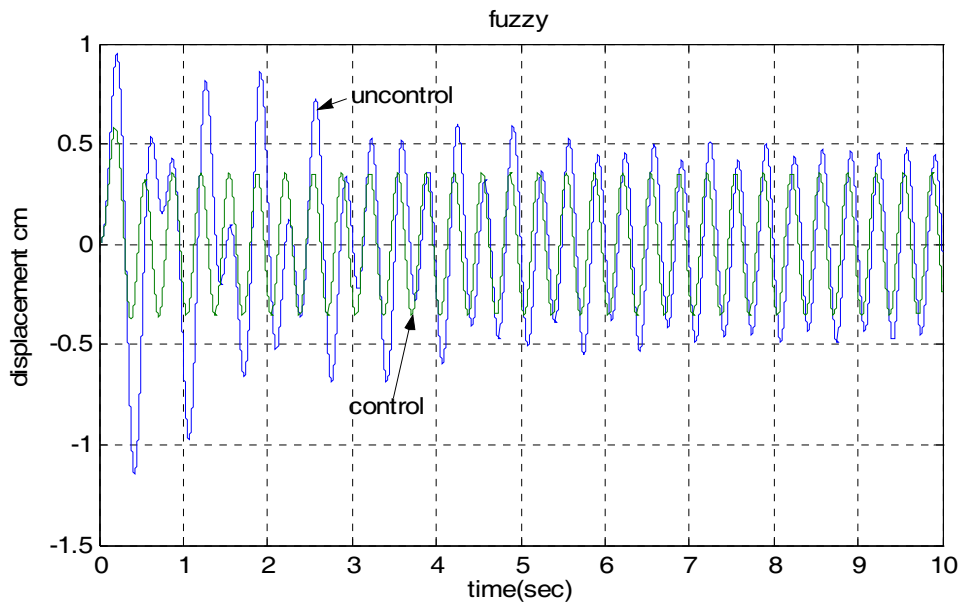
Figure 6 Simulation results (displacement) of Fuzzy controller of semi active suspension system for sinusoidal input disturbances.
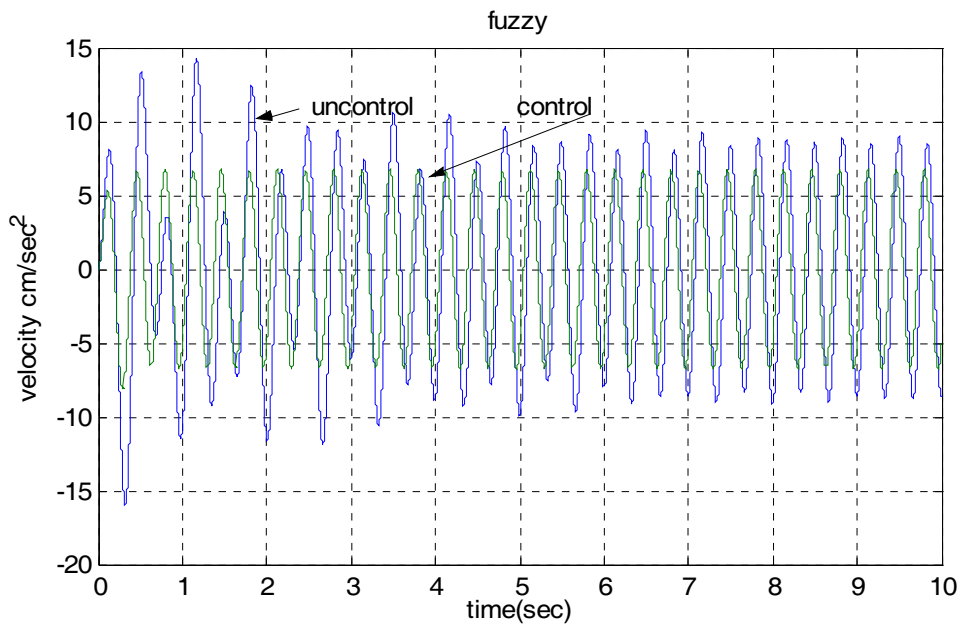

Figure 7 Simulation results (velocity) of fuzzy controller of semi active suspension system for sinusoidal input disturbances.
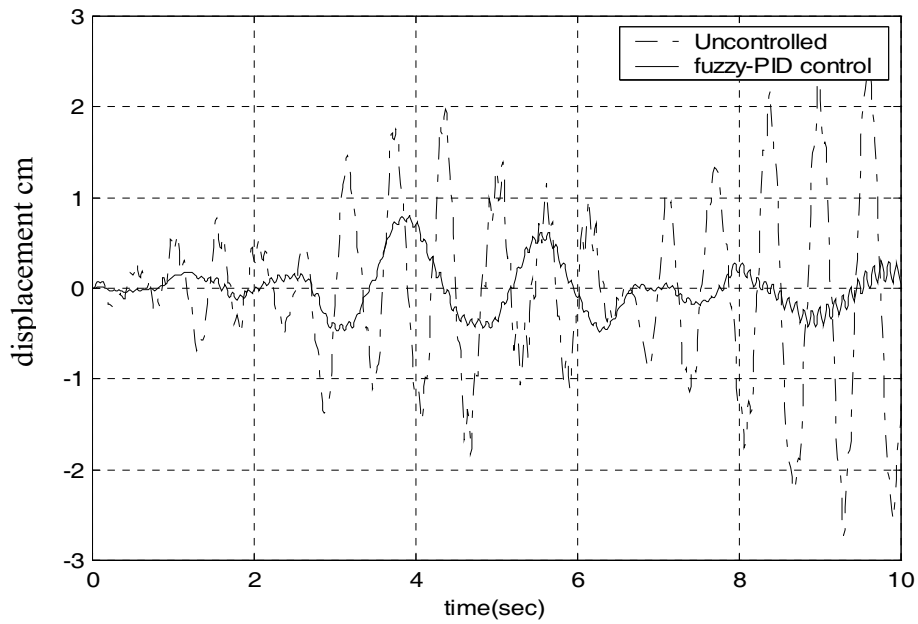
Figure 8. Simulation results (displacement) of fuzzy-PID controller of semiactive suspension system for random number input disturbances.
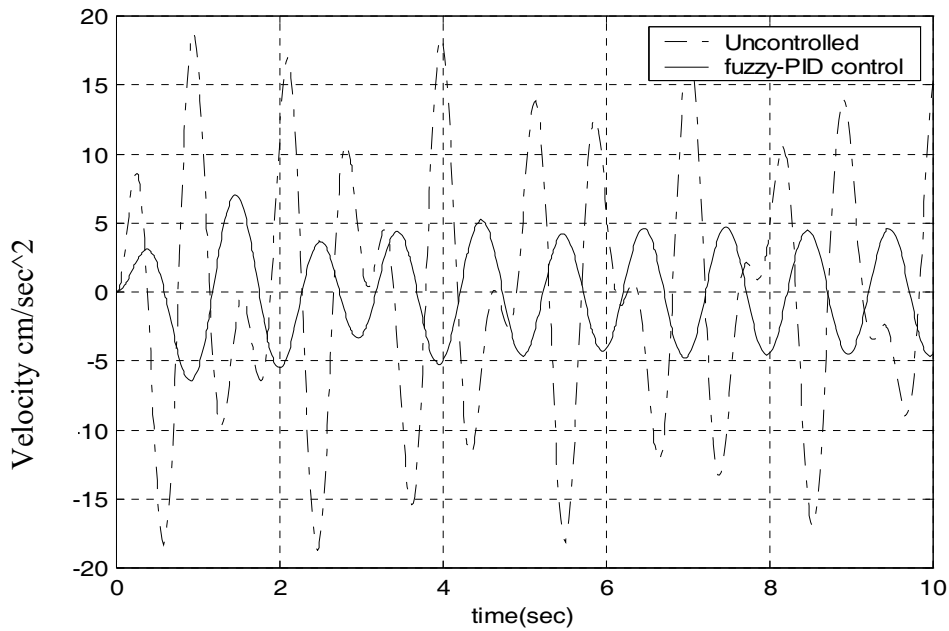

Figure 9 Simulation results (velocity) of fuzzy-PID controller of semiactive suspension system for random number input disturbances

From the simulation results (Figure 6 to 9), it has been observed that disturbances are eliminated partially, but the use of this controller do not give satisfactory results as required. So some modification will be carried out in the fuzzy and fuzzy hybrid controller to get better performance as described in next section, where MR damper model based suspension system will be developed using fuzzy and fuzzy hybrid controllers with gain scheduling. The gain scheduling of fuzzy controller will change directly with changes in road disturbances as seen in Figure 12 and Figure 13.

5. Fuzzy Controller with Gain Scheduling for Semi Active Suspension System:

Fuzzy gain-scheduling offers a simple yet robust solution to the problem of controlling a non-linear plant subject to large changes in its operating state. In this technique, fuzzy linguistic rules and fuzzy inference mechanisms are used to establish the required control policy. The input variables to the fuzzy controller are the sprung mass displacement (y) and difference of displacement between sprung mass and unsprung mass $(y - x)$ and the output as the applied current to the MR damper. The membership functions for the inputs were defined on the normalized universe of discourse [-1, 1] and selected as seven identical triangles with 50% overlap (Figure 10). Those for the output were defined on the universe of discourse [0, 1] and selected as four identical triangles with 50% overlap (Figure 11). The labels NL, NM, NS, ZO, PS, PM, PL refer to negative large, negative medium, negative small, zero, positive small, positive medium, and positive large, respectively. Rules for computing the desired current are presented in Table 2 (Liu et al.2001). Fuzzy rule used here is bit different from fuzzy rule used before, because modification of rule was necessary to run the controller effectively. Since the output's universe of discourse was normalized, a defuzzifier factor was required and chosen as $Ku = 3$.

The fuzzifier factors used to convert the inputs into fuzzy variables were defined as Kd and Kv, for displacement and difference of two displacement, respectively. To determine whether a relationship exists between these variables and the magnitude of the road displacement, an estimation work has been performed. According to these results, Kd was chosen as 5, since this value yielded the best results for all cases studied. No single value could be selected for Kv, however, the following relationship was observed: for scaled down versions of road disturbances, larger reductions in car body responses were obtained with small values of Kv, while for amplified versions of the road disturbances, larger values of Kv produced better results.

6. Gain scheduling

Based on the parameter analysis, the following equation 8 was determined for the gain scheduling of scaling factor Kv: where the value Kv is the absolute value of the road displacement. A diagram of the proposed gain scheduled system is presented in Figure 13 and 14.

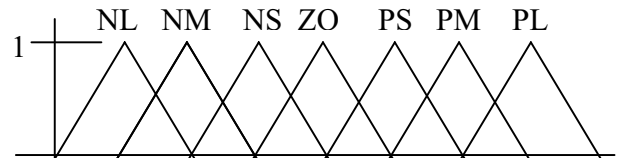$$K_v = 23.37|w| - 0.68 \qquad (8)$$

where w is the road input

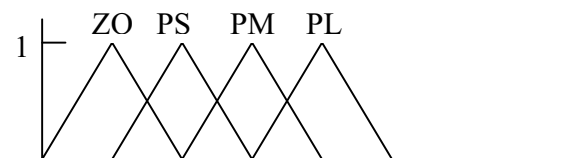Figure 10 input membership functions

Figure 11 output membership functions

Table 2 Rules for computing the desired current output

		(y-x)					
		NL	NM	NS	ZO	PS	PM	PL
	NL	PL	PL	PL	PM	ZO	ZO	ZO
	NM	PL	PL	PL	PS	ZO	ZO	PS
x	NS	PL	PL	PL	ZO	ZO	PS	PM
	ZO	PL	PL	PS	ZO	PS	PM	PL
	PS	PM	PM	ZO	ZO	PL	PL	PL
	PM	PS	ZO	ZO	PS	PL	PL	PL
	PL	ZO	ZO	ZO	PM	PL	PL	PL

Using the modified controller structure for semi active suspension system as seen in Figure 12 and 13, the simulation work have been carried out with different road disturbances.

Both fuzzy and fuzzy hybrid controller uses the same rule and membership function as stated above and the response of semi active suspension system using the PID, fuzzy and fuzzy-hybrid are shown in Figures 14 to 25.
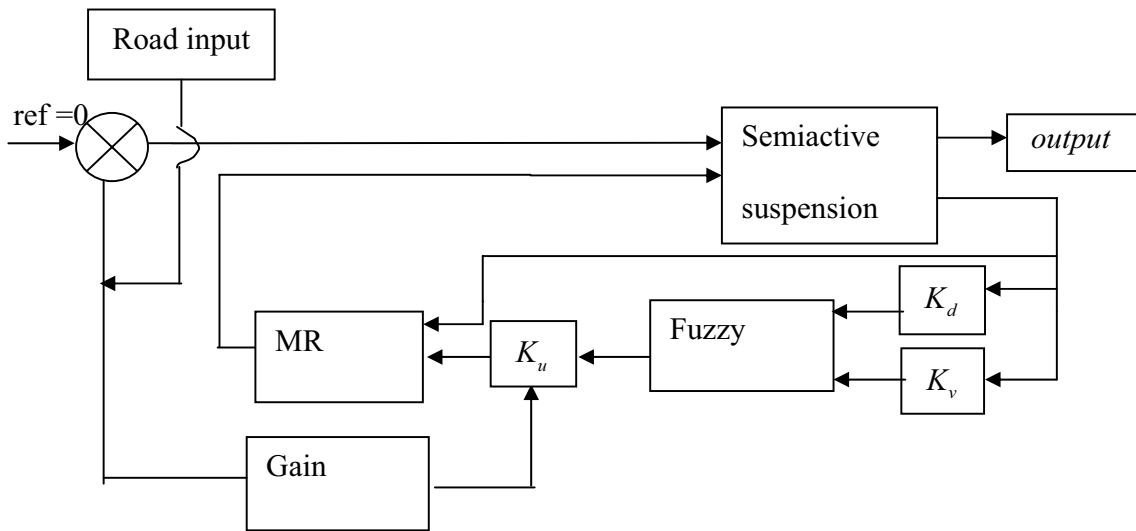

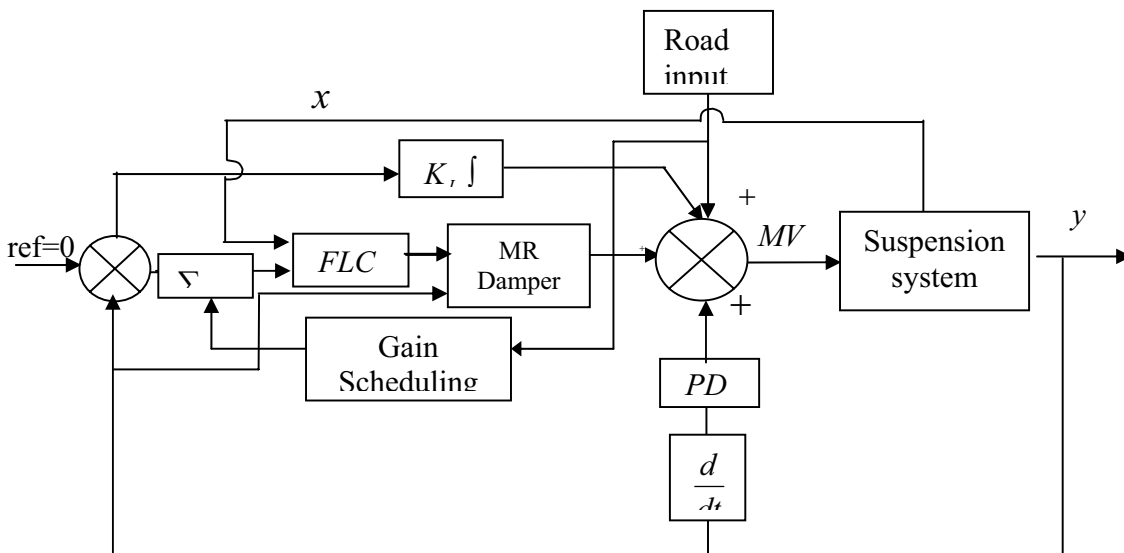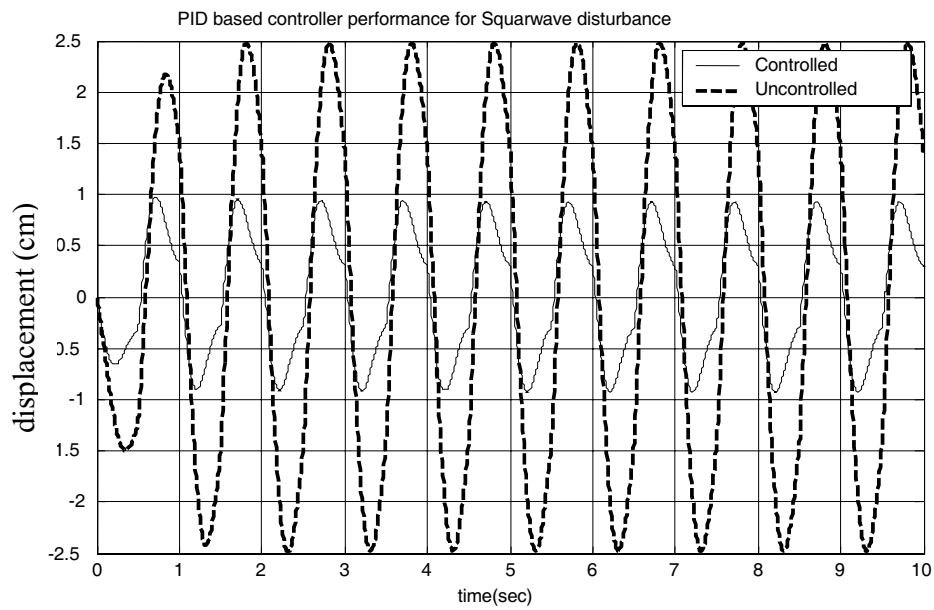Figure 12 Semi active suspension control model by MR Damper using fuzzy logic with gain scheduling.

Figure 13 Semi active suspension control model by MR Damper using fuzzy hybrid controller with gain scheduling.

Figure 14. Simulation results (displacement cm) of PID controller of semi active suspension system for square wave input disturbances
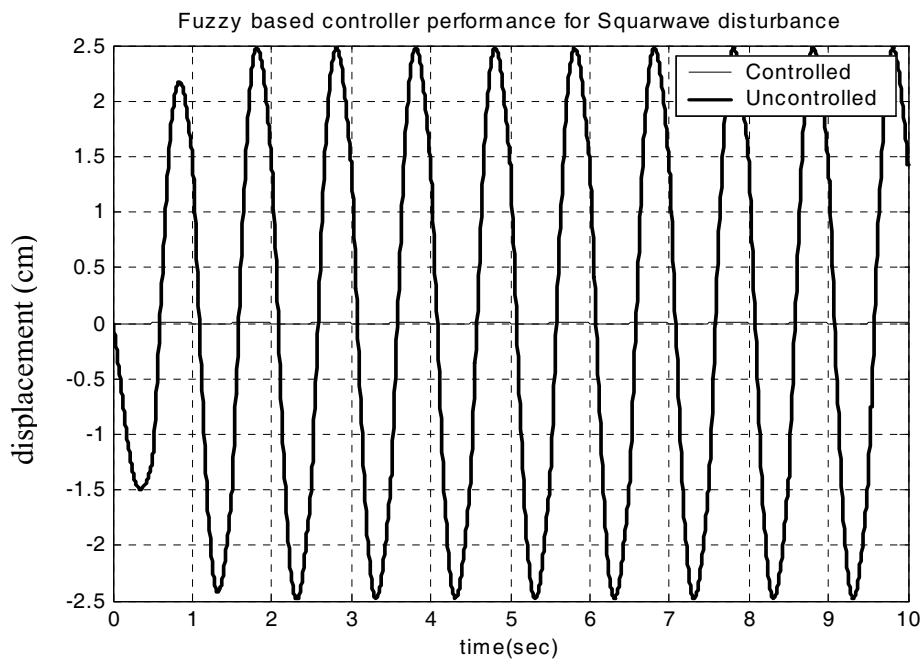

Figure 15. Simulation results (displacement) of Fuzzy with gain scheduling controller of semi active suspension system for square wave input disturbances
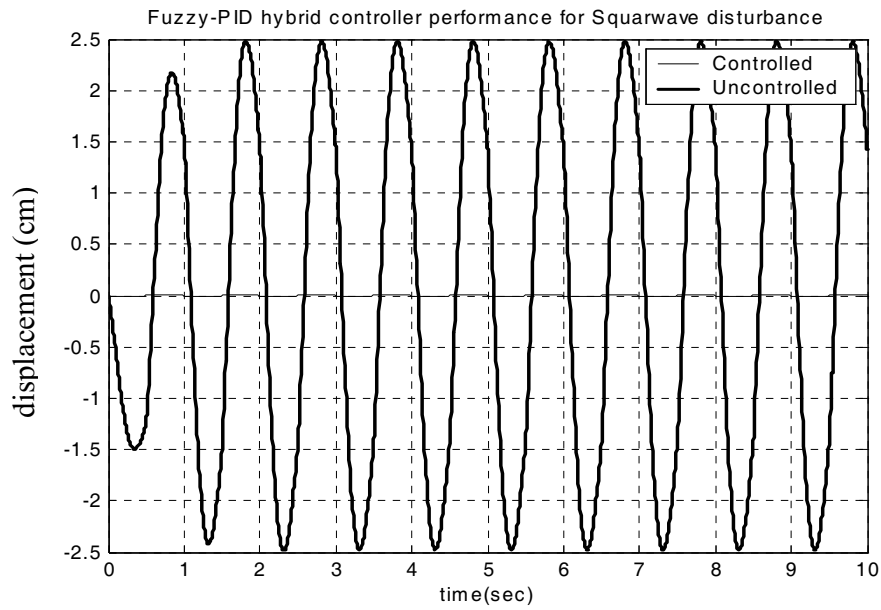
Figure16. Simulation results (displacement) of Fuzzy-PID with gain scheduling hybrid controller of semi-active suspension system for square wave input disturbances.
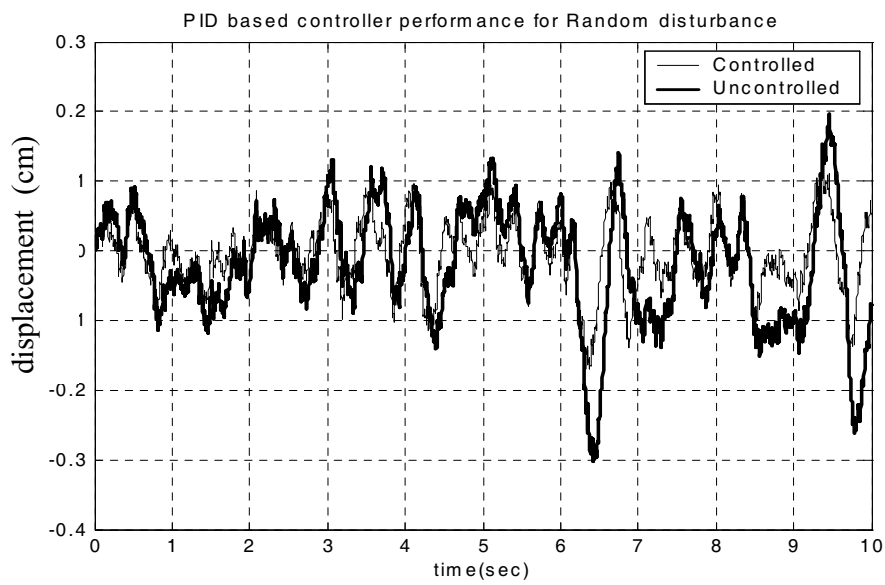

Figure 17. Simulation results (displacement) of PID controller of semiactive suspension system for Random input disturbances.
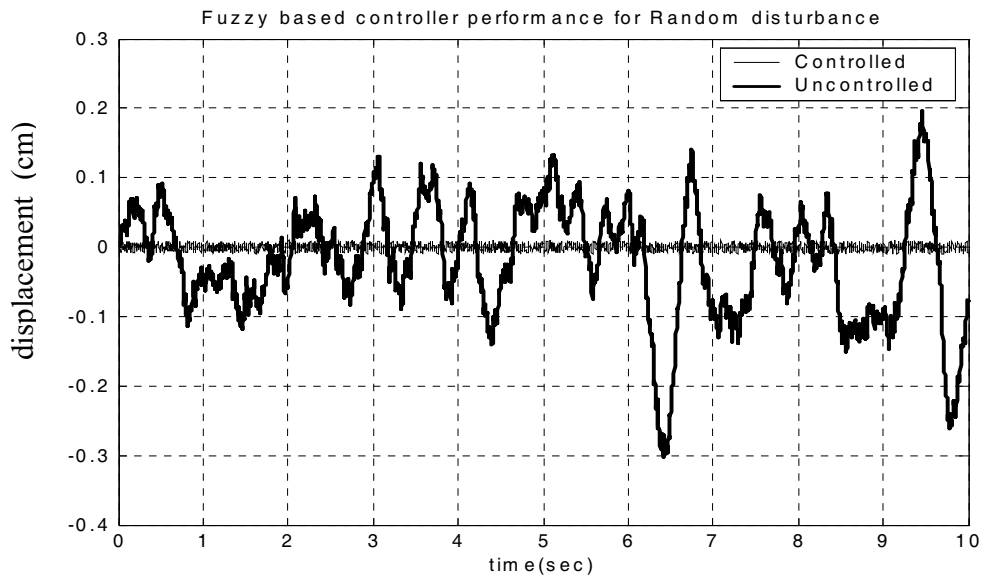
Figure 18 Simulation results (displacement) of Fuzzy with gain scheduling controller of semi active suspension system for random input disturbances
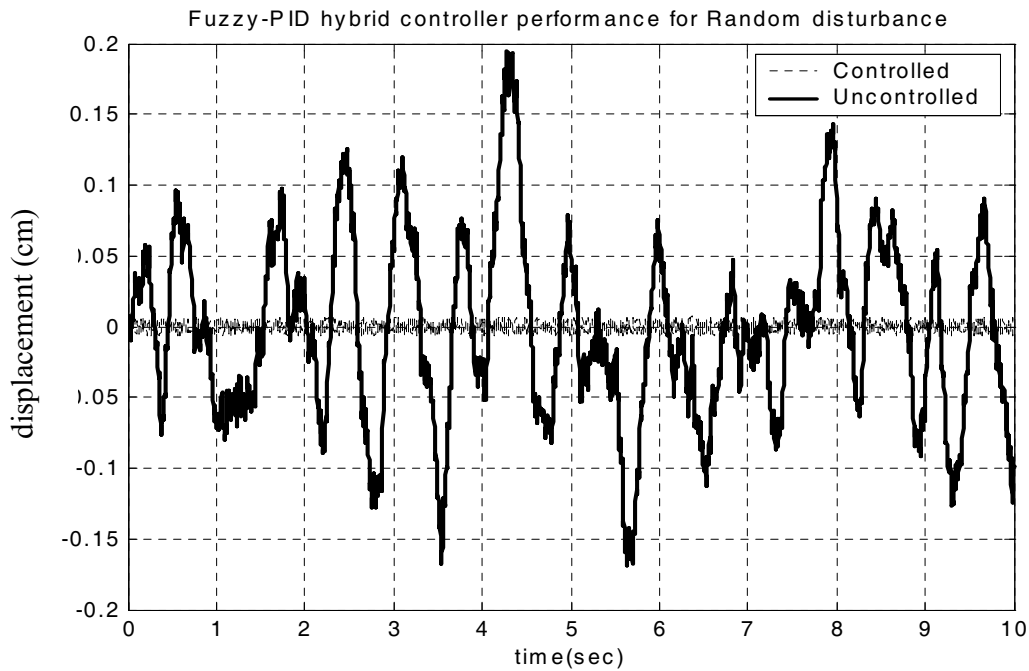

Figure 19 Simulation results (displacement) of Fuzzy-PID with gain scheduling controller of semi active suspension system for random input disturbances
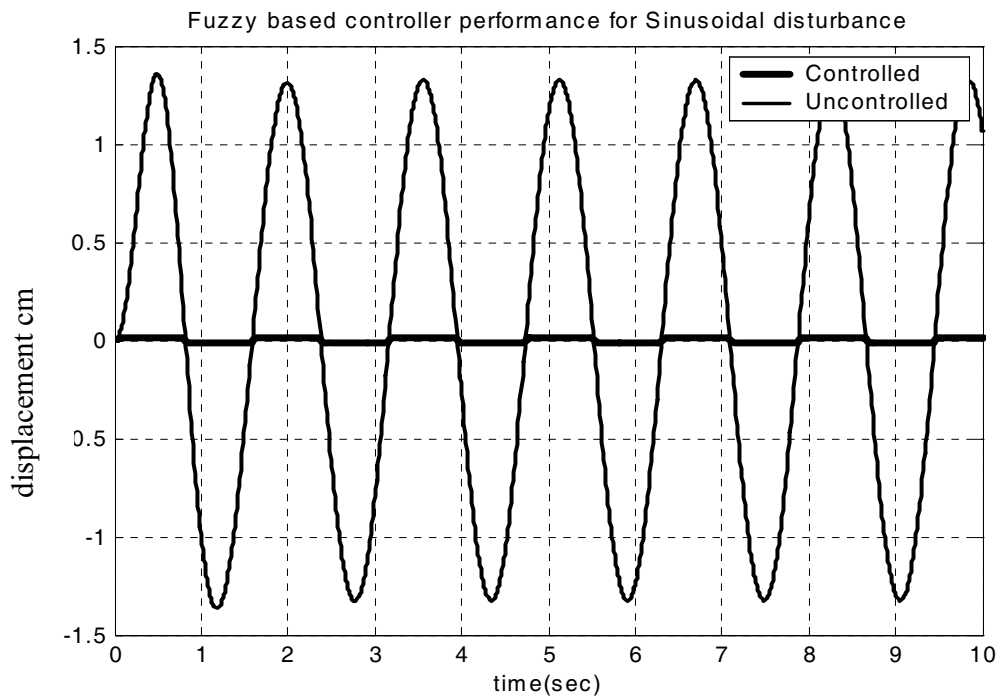
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Figure 20 Simulation results (displacement) of PID controller of semi active suspension system for sinusoidal input disturbances
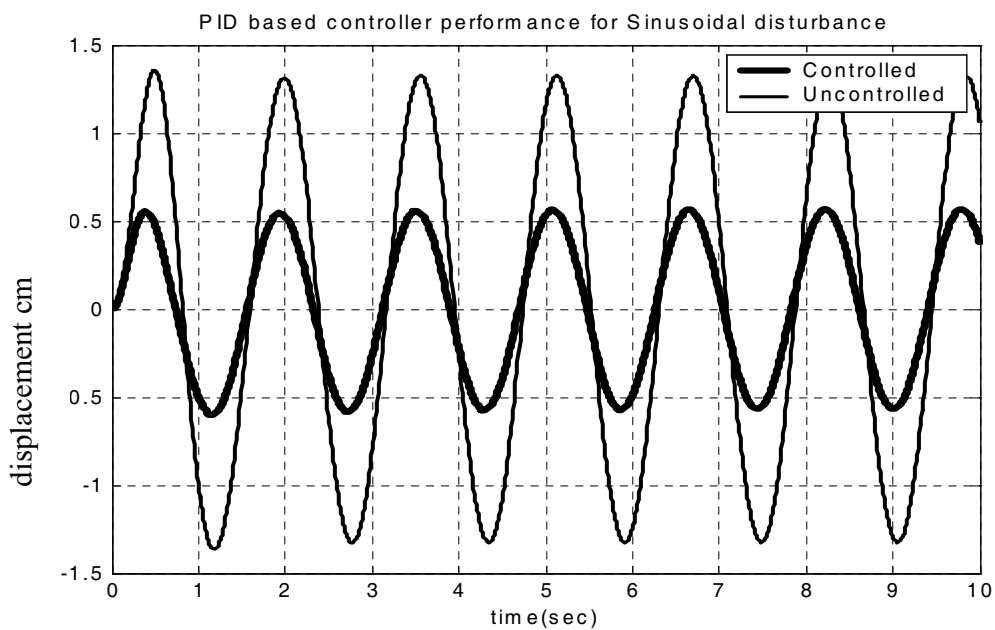

Figure 21 Simulation results (displacement) of Fuzzy with gain scheduling controller of semi active suspension system for sinusoidal input disturbances
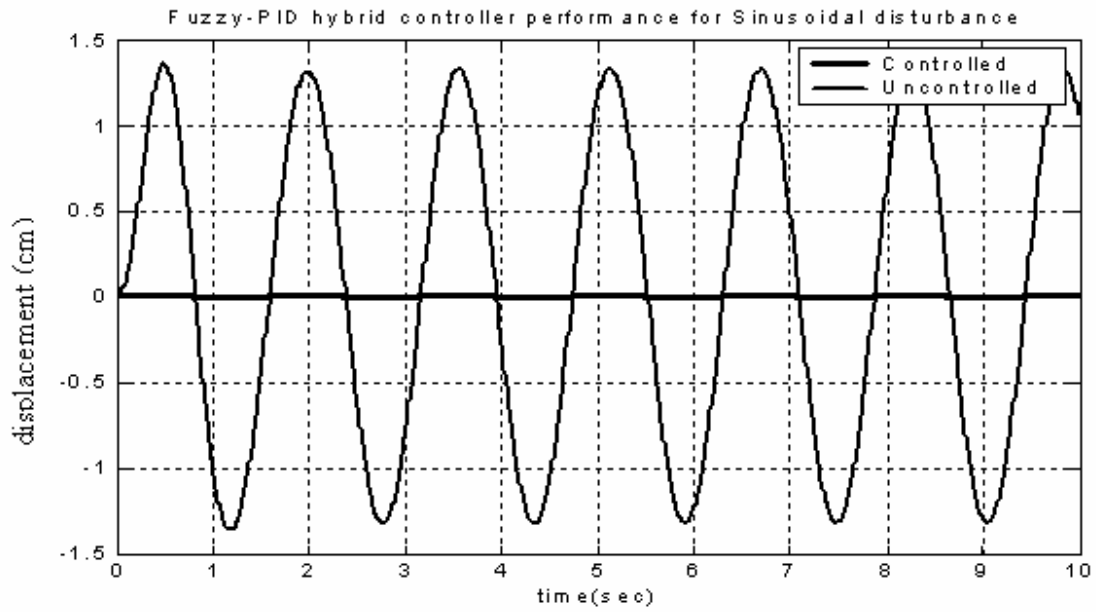
Figure 22 Simulation results (displacement) of Fuzzy-PID with gain scheduling controller of semi active   suspension system for sinusoidal input disturbances

Figure 23 Simulation results (displacement) of comparison of controller performance of semi active suspension system for square wave input disturbances

Figure 24 Simulation results (displacement) of comparison of controller performance of semi-active suspension system for random input disturbances
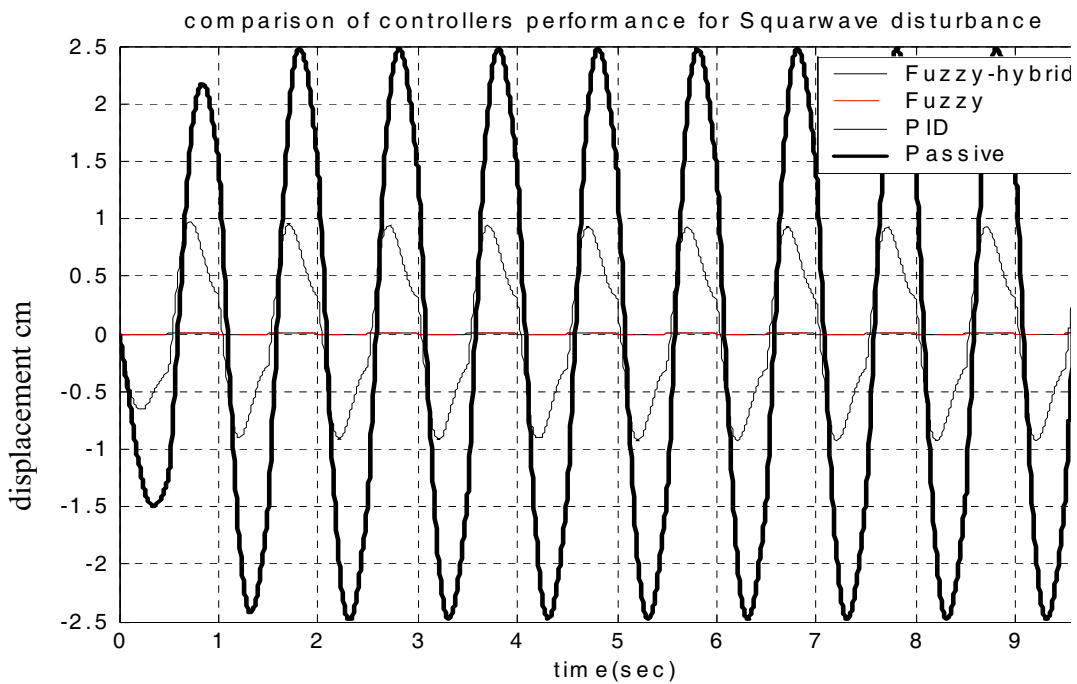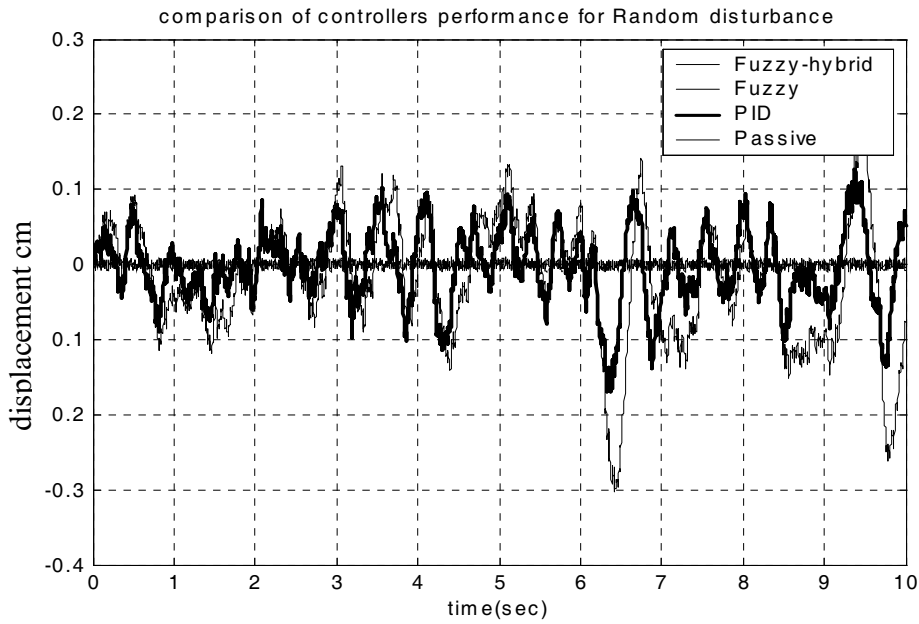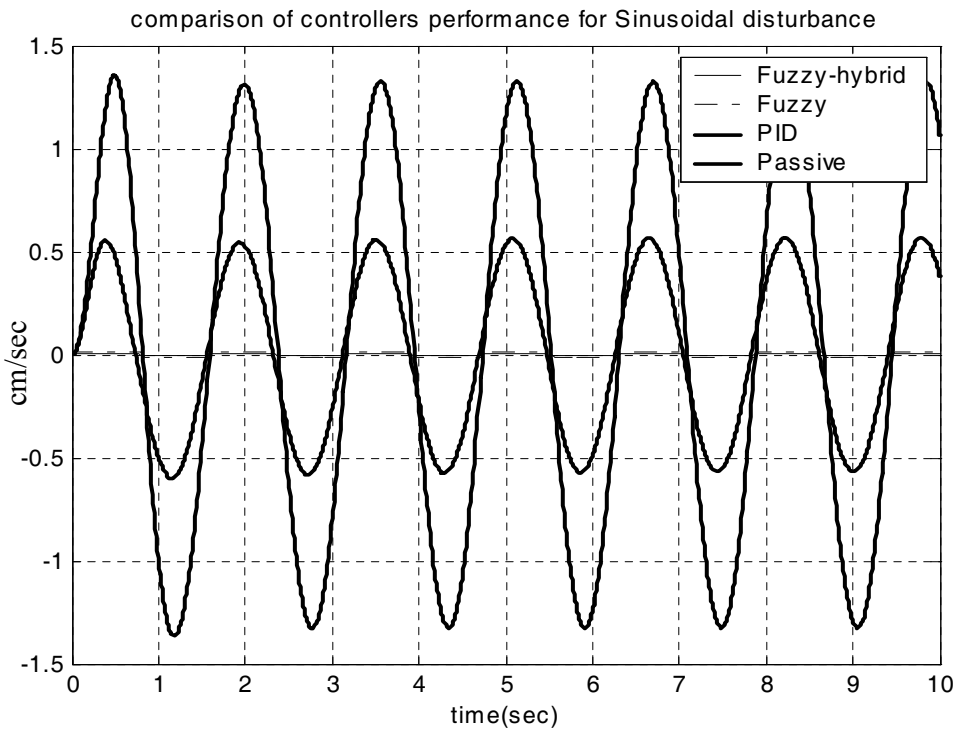

Figure 25 Simulation results (displacement) of comparison of controller performance of semi active suspension system for sinusoidal input disturbances

From the results obtained, it can be concluded that both controllers proposed were successful in reducing maximum amplitude of displacement and RMS responses of the semi active suspension system under three different load disturbances. The gain scheduled fuzzy and fuzzy-hybrid controllers were also found to be more effective than the simple fuzzy and fuzzy-hybrid controller as described in the previous section.

7. Discussion and summary

In this work, different types of controller are used for controlling the semi-active suspension system; controller's performance has been shown in detail graphically. The responses of MR damper model based semiactive using fuzzy-PID controller are shown in Figure 6 to 9. From these simulation results, it has been observed that disturbances are eliminated partly, but still

system contains some disturbances as seen. The gain scheduling of fuzzy controller have been developed on the semi active suspension system, using this controller and the responses of semiactive suspension system are shown in Figures 14 to 25 showing that the performance of controller is satisfactory.

In Table 2, the controller's performances are measured in terms of amplitude of displacement and IAE of displacement. This quantitative result enables one to understand the controller's performance easier than the graphical result. From the Table 2 it appeared that the Fuzzy controller able to reduce the amplitude of disturbance from 87 to 90% and to reduce IAE from 73 to 81%, the Fuzzy-hybrid controller was able to reduce the amplitude of disturbance from 90 to 92% and to reduce IAE from 78 to 80%. From the available data in the table 5.4, it has been found that fuzzy and fuzzy-hybrid controller's performance was better than PID

Table 3 Comparison study of different controller

Displacement amplitude analysis			
Fuzzy with gain scheduling			
MR semiactive suspension system with sinusoidal road disturbances	Controller	Reduction%	IAE
	Fuzzy	90	190
	Fuzzy-hybrid	92	180
MR semiactive suspension system with square wave road disturbances	Fuzzy	89	240
	Fuzzy-hybrid	90	240
MR semi active suspension system with Random road disturbances	Fuzzy	90	251
	Fuzzy-hybrid	90	250

After modification of the controller, adding gain scheduling to fuzzy input with respect to road input, the controller was able to eliminate disturbance efficiently. Damping coefficient was varied by the controller's action (PID, Fuzzy and Fuzzy hybrid) to control suspension. In this modeling part, it has been possible to get the satisfactory result especially in the case of Fuzzy and Hybrid-fuzzy. Some analysis of controllers result have been done and included in the Table 3 which is the comparison study of different controller.

8. CONCLUSIONS

In this study, the effect of a MR Damper for suspension control was investigated. The characteristics of the MR damper are studied here. The damping coefficient of the MR damper in terms of input current, displacement amplitude and frequency are examined. In this paper, the new semi-active suspension control system is proposed to achieve both ride comfort and good handling. This aim was

achieved with respect to the results of the simulation; the results of the semi-active suspension system based on the fuzzy logic controller also show the improved stability of the one-quarter-car model. The results presented in this work are quite self-explanatory justifying that the semi-active MR suspension system can be effectively employed to the passenger vehicle with improved both ride comfort and steering stability. This would encourage that the use of the MR damper increase vehicle stability and to control suspension.

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