A New Fuzzy-NARMA L2 Controller Design for Active Suspension System

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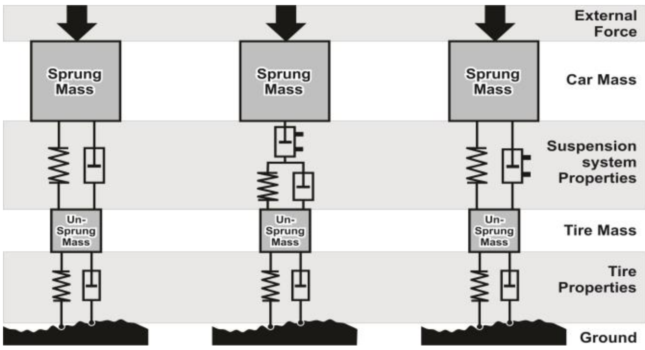
Abstract- **This paper is concerned with the design of a new controller for active suspension system. The model is considered as a quarter-car. The presented controller depends on the fuzzy technique and NARMA-L2 linearization algorithm. The compensation system that added by the fuzzy rules improves the performance of the controller, while the neural network produces the required control signal. The new controller can achieve an improvement of the ride comfort with a reasonable value of power consumption. The mathematical analysis of the mechanical power used by the model is focused on the average and the RMS of the power supplied to the system, regardless of the frequency content of the vibration signal. The simulation results which are verified by a practical examples of road profiles, demonstrate the efficacy of the proposed controller.**

Keywords: vehicle, suspension system, control, rider comfort, fuzzy, NARMA-L2

I. Introduction

Recently, rider comfort plays an important role in civil and military vehicles. Riding comfort can be defined as transportation of human in an easy manner. Most of the suspension systems depend on the basic spring damper system. Some of recent researchers focus on changing the value of the damping coefficient. This method is called semi active suspension. On the other hand, the second type is performed by applying force between sprung and unsprung mass. This type of suspension system is called "Active Suspension" which is the subject of the paper, see fig. 1.



a- passive b- semi-active c- active

Fig. 1 Types of Suspension System.

Active suspension system designs have to reduce suspension deflection a well as the vertical acceleration. This will require a continuous contact between the road and wheel rim. This, in turn, will help to improve braking efficiency and the vehicle maneuverability. The requirements for improved suspension systems are to prevent road disturbances, rider comfort improvement, riding capabilities, and smooth driving.

The energy consumed on active suspension system is one of the main governing factors that should be considered during driving operation to save energy and, hence, more driving time. Vehicles were considered to carry limited energy storage for maneuver and implementing certain tasks. The battery or fuel is the most common used sources of energy in vehicles. They are limited in storage, for that reason it is important to study how much power will be spent in active suspension system

The principle behind active suspension system is the utilization of active element such as hydraulic cylinder or magnetic actuator. The role of this element is to apply a certain amount of force to keep the vehicle at a comfortable situation. The car computer units compute this force under road abnormalities (disturbances) to keep a certain objective of comfort level. This type of system require a lot of components such as actuators, servos, pressurized tanks, accelerometers, distance sensors, ... etc [1]. Control system is powered by vehicle engine which may be high at the expense of required performance [2].

This subject of control is considered as one of the highest difficult problems due to the complex relations between system variables. For this reason, it attracted many researchers to study it to improve the rider comfort. Researchers used many control schemes like PID, LQR, LQP, H∞, …. Etc [3]. In the current paper, PID, NARM-L2, and Fuzzy Logic Controller will be implemented. Since there is a little research effort in the above field, only relating literature will be reviewed.

Ekoru et al [4] studied on half car model 4-DOF and designed two loop control system. The two loops were nested with inner one was PID actuator force control loop, while the outer was PID deflection control loop. They compared the results with passive system and results showed that the active system had superior performance. Avesh and Srivastva [5] improved the ride comfort of a vehicle modeled using half car 4-DOF Model. The modeling and simulation was performed using MATLAB Simulink environment. They reported in their paper that the rider comfort was significantly improved using this PID controller. Based on half car Simulink model, Talib and Darus [6] studied the effect of road abnormalities on active suspension system with PID controller. Different road disturbances like bump-hole, sine, and random input were studied. Three PID tuning methods Zeigler-Nichols, iterative learning algorithm, and heuristic tuning were used. As usual, the active suspension system was compared with passive one and results showed that active system had higher efficiency. The iterative learning tuning proved that it was the better one from the other tuning method used. To improve vehicle ride comfort and for the controller to be more reliable and adaptable on change of plant parameters, Jinzhi et al. [7] proposed a PID controller which is tuned with Genetic algorithm (GA) on 4-DOF vehicle model. GA was not only used to tune the parameters of the PID but also used as scaling factor, gain values, and membership functions of the fuzzy controller. They proposed a two-loop controller system. One loop was PID was used to reduce the body vertical acceleration. and the second one which was Fuzzy logic controller was used to minimize the pitch acceleration. The results showed that this type of controller was very effective in the reduction vertical acceleration. Eski and Yildirim [8] designed their active suspension control system on full vehicle and applied it to random road roughness. The system was based on a robust controller, neural controller, and neural network for identification of the suspension system. They also used the PID controller as well. They proved that the neural network controller was better than conventional PID controller. Zhu et al 2014 [9] focused on the development of hyrdraulically interconnected suspension system (HIS) model. To validate their model, two experiments and their corresponding simulations using MATLAB SIMULINK were conducted. The comparison between the experimental and simulation results showed high consistency in robustness and accuracy.

Ro et al [10] applied a feasibility study for active suspension system . The modeling and simulation were done on a quarter car model with Fuzzy logic controller. They proved that the velocity and acceleration were the most useful states of the Fuzzy logic controller. The results were compared to LQ optimal controller and the passive case then advantages and limitations were listed. Other authors like Rajeswari and Lakshami [11] used PSO optimization method to find the optimal parameters of fuzzy logic controller. They designed two controllers the first was the conventional FL controller and the second was FL controller tuned with PSO. The results were compared in regard of the sprung mass acceleration and proved better performance of the optimized FL controller. Other researcher like Chiou eand Liu [12] tuned the fuzzy logic controller using genetic algorithm (GA). The influence of the GA was done on membership functions and control rules. The results showed in this paper that rider comfort and stability was better than systems with conventional control schemes. Some researchers like Rao et al. [13] used fuzzy logic controller to minimize the rider comfort. They studied the rider comfort of 3-DOF quarter car model and measured the acceleration of the rider body and compared to ISO-2631-1:1997(E). Results showed much improvement of the rider comfort of fuzzy logic controlled active suspension to that of passive suspension.

Attempts to mix between FLC and other types were studied in many literature. Lin et al [14] studied the application of fuzzy sliding mode controller (FSMC) to quarter car active suspension system. The results showed that the FSMC didn't improve the results of the Traditional FC. However, They approved that Enhanced Sliding mode control showed better performance in the rider comfort.

Al-Holou et al [15] designed a combination controller of sliding mode, fuzzy logic and neural network for the active suspension system on quarter car model. The results showed that the designed controller performed better than every conventional control scheme alone. In a paper published by Yagiz et al [16], they used 5-DOF quarter model to test three types of controllers namely first one is passive system the second is active suspension with passive seat and the third one is active suspension for both seat and suspension They preferred the third case due to its higher efficiency in isolation of road irregularities. Unlike the previous literature, lieu et al [17] used fuzzy logic controller for quarter car experimental rig. They used a high speed on-off controller to fire the solenoid valve using FLC. They showed that the amplitude of vibration was reduced to 55%. Yoshimura and Tanagi [18] applied fuzzy reasoning and a disturbance observer for the control of quarter car model. Researchers proposed to insert a phase lead-lag compensator to improve performance due to delay in pneumatic actuator. A fuzzy logic controller for the Takagi–Sugeno (TS) fuzzy model based systems was also studied by some researchers like [19] [20] [21] . This is because T-S fuzzy logic controller is efficient in handling system with nonlinearities. The researchers showed a lot of results on synthesis, stability, and filter design for this type of fuzzy logic controller. Most researchers extensively use quarter car in automotive study because it is simple and it provides correct information during the initial design process [22].

The Presented paper is divided into three main parts: the first part contains the study of active suspension system besides the derivation of the linear suspension model. Then a Matlab model is built in this part. The second part will deal with building and design of a new Fuzzy-NARMA controller and compare it to various controllers for this type of systems. The job of the first stage of the NARMA model is performing the identification of our system. In the third part, a study of the mechanical power consumption in the actuator will be implemented. Equations for the instantaneous and total power consumed during simulation session will be derived.

The implementation of the new controller is done and compared on simulation with the well-known control scheme, the PID controller. The simulation platform MATLAB Simulink was used for the implementation. Simulation process was used for testing the controller because hardware changing is very difficult and expensive when the system is not working properly.

II. POWER CONSUMPTION IN ACTUATOR

There is no much literature to study the mechanical power consumed in the vehicle with active suspension system. Most papers calculate the overall power instead of that consumed only on the actuator [23] . Instantaneous mechanical power is defined as [24]:

$$P(t) = F(t) * v(t) \quad (1)$$

where *F(t)* and *v(t)* are the instantaneous Force and velocity on actuator respectively.

Generally, the average consumed mechanical power will be considered here; this is usually done using the time integral on the simulation period divided by that period [25];

$$P_{avg} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} F(t) v(t) \, dt \quad (2)$$

This method for the calculation of power gives the total mechanical power regardless of the frequency content of the vibration signal. Due to modern computerized control system, this is performed digitally;

$$P_{avg} = \frac{1}{n} \sum_{k=1}^{n} F(k) v(k) \quad (3)$$

Another type of averaging is to find the RMS mechanical power supplied to the system, which is found from the following formula [25]:

$$P_{RMS} = \sqrt{\frac{1}{t_2-t_1}\int_{t_1}^{t_2}[F(t) * v(t)]^2 dt} \ldots\ldots\ldots\ldots\ldots\ldots.. (4)$$

III. NONLINEAR AUTOREGRESSIVE MOVING AVERAGE (NARMA L2) CONTROLLER

The NARMA model is considered as exact mapping of the input output behavior of a finite dimensional and nonlinear discrete time dynamic system near the equilibrium condition. Because of the nonlinearities it cannot be applied to control systems working in real time. Solving this issue evoked by using of ANN in advanced control strategies two models of NARMA are proposed in [26] NARMA L1and NARMA L2 depending on the linearization algorithm The second model is more applicable to be implemented by using artificial neural networks (ANN).

The principle behind NARMA L2 controller is transforming the nonlinear system into a linear system by elimination of the nonlinearities which makes it appropriate for control of nonlinear systems. NARMA L2 is done by rearrangement the ANN of the controlled system and then the training process is done off-line in a batch mode. Therefore, in designing of NARMA L2 controller, it must identify the system to be controlled. The Second norm of NARMA L2 is used to represent discrete system [26] as follows;

$$y(k+d) = N[y(k), y(k-1), \ldots\ldots, y(k-n+1), u(k), u(k-1), \ldots., u(k-n+1)] \ldots\ldots\ldots\ldots\ldots(5)$$

The NARMA L2 Norm Narendra [26] is represented by the following equation;

$$y(k+d) = f[\,y(k), y(k-1), \ldots\ldots, y(k-n+1), u(k-1), \ldots., u(k-m+1)] + g[\,y(k), y(k-1), \ldots\ldots, y(k-n+1), u(k-1), \ldots., u(k-m+1)]u(k) \ldots\ldots\ldots(6)$$

IV. THE PROPOSED CONTROLLER

IV.I MATHEMATICAL MODEL

A new model has been implemented in this study as shown in Fig.2. The model is considered as quarter car representation where the displacements of car body (x_1) and wheel x_2 are measured by two sensors. Also, the speed of car body ($\dot{x}_1$)and wheel ($\dot{x}_2$) are measured as a two inputs to the control system. The four signals are sent to an intelligent processing system based on neural network and fuzzy logic techniques. Neural network produces the required control signal depending on the variation in the net vibration deflection ($x_1 - x_2$) that occurs between the car body and the wheel. In order to improve the efficiency of the controller, a compensation system has been added to the model based on fuzzy logic scheme. This assist system receives the signal as from two accelerometers to treat the net acceleration ($\ddot{x}_1 - \ddot{x}_2$) as a first input and the signal from the neural , then, by acceptable rule base it can produce the required compensate control signal to teach the set point of the net vibration of plant. The differential equation of the proposed model can be written as:

$$m_1\ddot{x}_1 - c_1(\dot{x}_1 - \dot{x}_2) - k_1(x_1 - x_2) = F_1 \ldots\ldots\ldots\ldots\ldots..(7)$$

$$m_2\ddot{x}_2 - c_2(\dot{x}_2 - \dot{x}_3) - k_2(x_2 - x_3) - c_1(\dot{x}_1 - \dot{x}_2) - k_1(x_1 - x_2) = F_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

Where model values are found in table 1.

TABLE 1
NUMERICAL VALUES OF MODEL PROPERTIES.

Variable	Value	Unit
m_1	290	kg
m_2	59	Kg
c_1	3600	N/m/s
c_2	15020	N/m/s
k_1	16182	N/m
k_2	190000	N/m

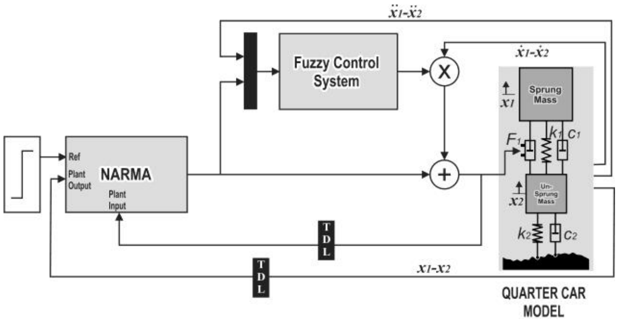


Fig. 2 Proposed Plant Controller

The Fuzzy inference controller with two inputs and one output is presented in this research. The inputs are output of NARMA-L2 controller and the net acceleration and they are denoted by input1 and input2. The output is the compensate control signal and it expressed by output1. Membership functions for input variables and output variable are introduced as shown in Fig. 3.

On the basis of the actuator force demand control strategy presented in this paper, 49 If-Then rules are developed which construct the fuzzy rule base of the fuzzy controller. These rules are shown in Table 2.

TABLE 2 THE FUZZY RULES.

AND		Output of NARMA-L2 controller							compensate control signal
		vvs	vs	s	m	h	vh	vvh	
Absolute of net acceleration	vvs	vvs	vs	s	m	h	vh	vvh	
	vs	vs	s	m	h	vh	vvh	vvh	
	s	s	m	h	vh	vvh	vvh	vvh	
	m	m	h	vh	vvh	vvh	vvh	vvh	
	h	h	vh	vvh	vvh	vvh	vvh	vvh	
	vh	vh	vvh	vvh	vvh	vvh	vvh	vvh	
	vvh	vvh	vvh	vvh	vvh	vvh	vvh	vvh	
	compensate control signal								

Where;
vvs: very very small
vs: very small
s: small
m: medium
h: high
vh: very high
vvh: very very high

Mamdani type fuzzy system has been used in this controller. The logical AND has been implemented with the minimum operator, the implication method is minimum, the aggregation method is maximum, and the defuzzification method is Largest of maximum.

Four strategies are usually considered to derive the rules of fuzzy control systems in most applications [27,28]. The experience of the expert is one of the main methods that is implemented in this study. Also, the relation of inputs with outputs can be very effective for making decisions and improve human skilled. However, this scheme requires an

adequate experimental data which are not available in this work. The third method which is applied in this paper is process behavior and its modeling with fuzzy logic. Finally, these rule base can be selected by learning methods such as neural network with then will be named as neurofuzzy technique.
The memberships of fuzzy controller can be defined as functional or numerical representation. However, in this paper, some acceptable functions are used and the main parameters are optimized based on the behavior of the plant model and the experience.
There are many methods used for tuning PID controllers such as genetic algorithm and fuzzy logic. However, in this work Zeigler and Nichols method is used which is available in the Matlab software and it can produce acceptable results that proves a sufficient accuracy for implementation a such comparison with the proposed model.

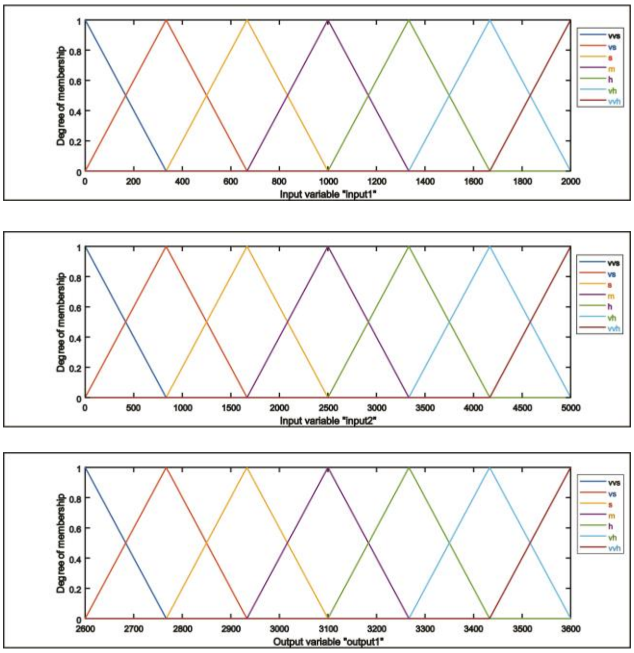


Fig. 3 Membership Functions of Input and Output Signals

IV.II SIMULINK MODEL OF PLANT AND CONTROLLER

The Simulink model of the plant is shown in fig. 4. The model is designed to produce any required variable such as net displacement $(x_1 - x_2)$ net velocities $(\dot{x}_1 - \dot{x}_2)$ and net accelerations $(\ddot{x}_1 - \ddot{x}_2)$. This model represented a solution of two differential equations solved by Runge-Kutta in Matlab Simulink. This model allow NARMA controller to obtain input–output data in order to train it with the help of (ANN) to make the control system be predictable to any variation of the plant vibration. The plant model and the proposed control system is assembled in the overall model shown in fig. 5. In this model, NARMA L2 controller is used as a main controller of the system. Fuzzy logic of two inputs and one output is considered as a correction part to compensate the error caused by some erratic road shapes.

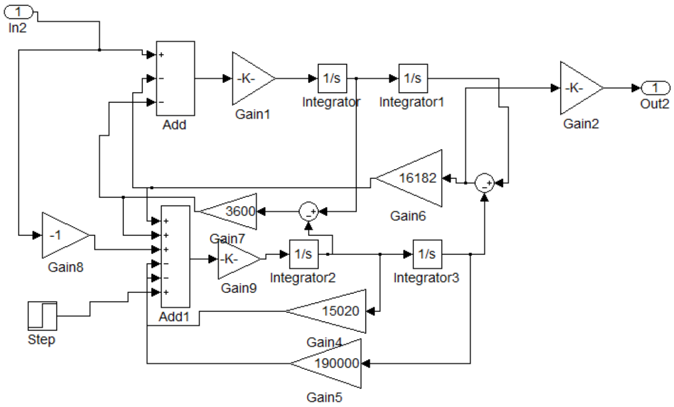


Fig.4 Plant model

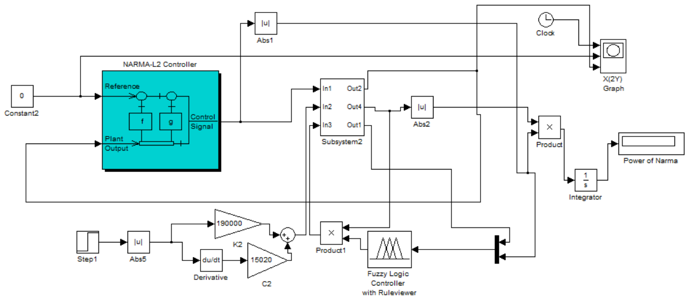


Fig.5 Simulink model of plant and controller

V. RESULTS AND DISCUSSION

The presented scheme was tested at various road shapes (Fig.6) and set points. However, in order to begin with this test, the plant identification must be implemented which starts by generating training data using the plant model shown in Fig.4. The data were generated with maximum interval value of (4 sec) and minimum interval value of (0.1 sec), where the sampling interval is chosen as (2 sec). About (8000) training samples were considered in order to be sufficient to train the network with (300) epoch. As shown in Fig.7, Narma-Fuzzy technique appear low overshoot as compared with Tuned PID , especially when subjected to sudden disturbance after (14 sec) .Also, it is noticed that Tuned PID produce undesirable peak value of response which is very danger in vibration applications. Although small interval of changing in the reference value , the proposed model makes high performance to treat this sharp edges. As compared with passive control suspension type (Fig.8), Narma-fuzzy technique shows intelligent prediction and acceptable fitting and produce better stability at (16 sec) when sudden step road shape occurs. Fig.9 shows the range of efficiency that the new scheme produce against some of other control types. The net vibration $(x_1 - x_2)$ usually setting at zero. In this case, when a step road shape was supplied to the model at (12) sec, it is clearly appearing that the blue color which represent new scheme is better than that of tuned PID,Fig.10. Also, Fig.11, shows high difference between passive and active control at the time of load applying. In order to avoid accumulative error, the model is tested with periodically road shape and compared with some different kinds of control, Fig.12, Fig.13 and Fig.14. Smoothly behavior in the net acceleration is very important in the suspension applications which can be achieved successfully with Narma-Fuzzy combination a shown in Figs. (15)and (16).

(a)

(b)

(c)

Fig.6 Road Abnormalities

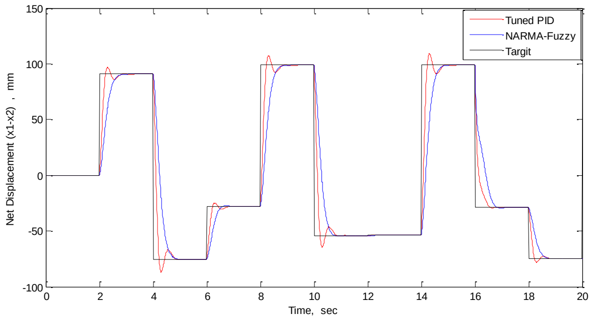


Fig.7 Comparison between proposed model against Tuned PID at variable reference case.

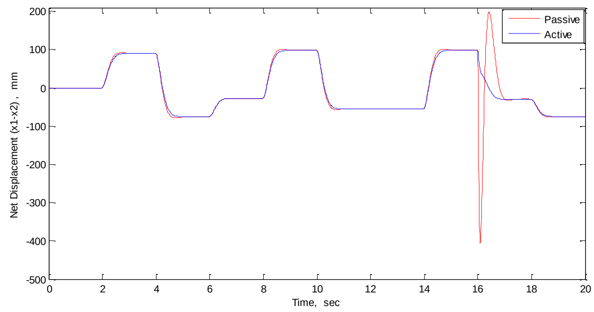


Fig.8 Comparison between proposed model against Passive control at variable reference case.

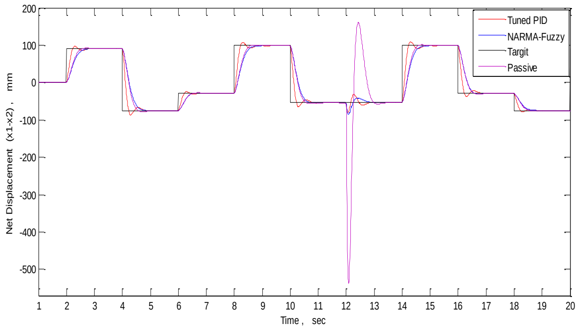


Fig.9 General test of proposed model at variable reference case.

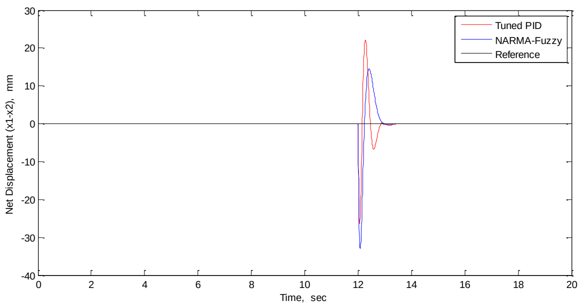


Fig.10 Comparison of proposed model against Tuned PID at zero reference case.

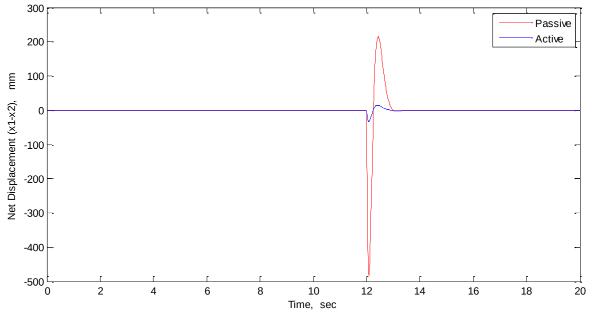


Fig.11 Comparison of proposed model against Passive control at zero reference case.

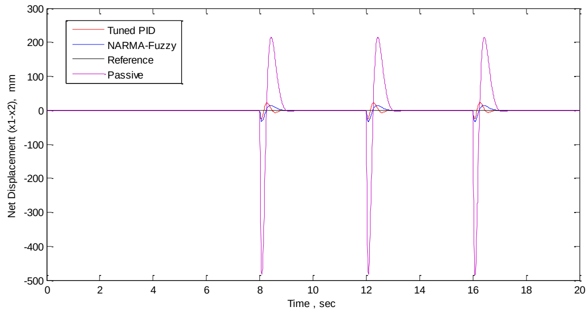


Fig.12 General test of proposed model at access disturbances.

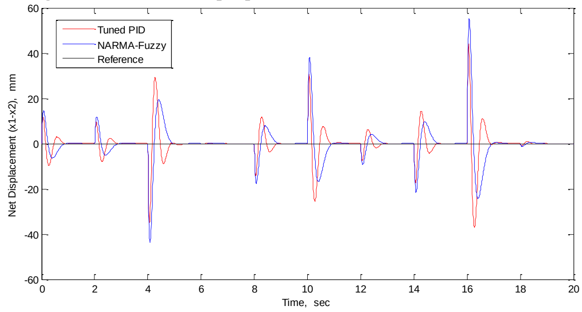


Fig.13 Success of proposed model when subjected to disturbances at various simulation time.

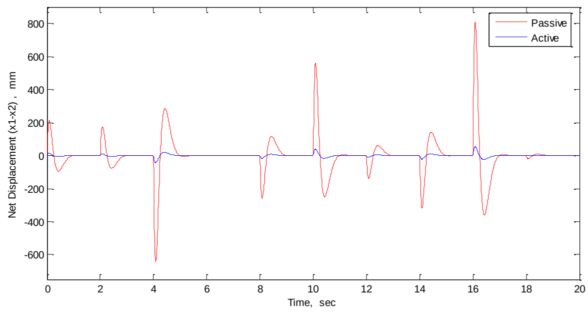


Fig.14 Performance of proposed model against Passive control when subjected to disturbances at various simulation time.

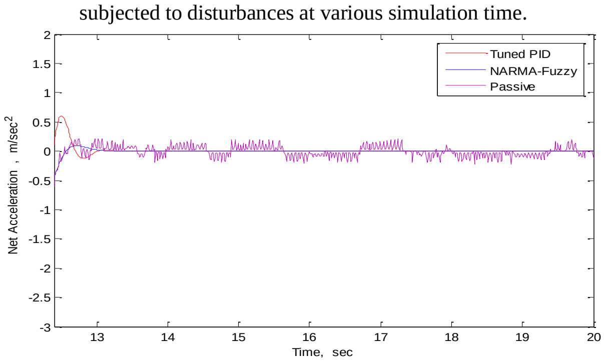


Fig.15 Accelerations of proposed scheme compared with the others due to step road shape.

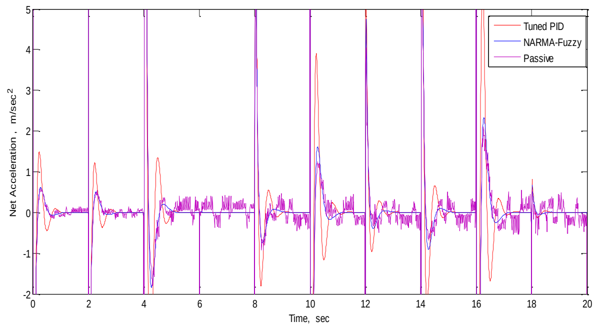


Fig.16 Accelerations of proposed scheme compared with the others control types at uniform random road shape.

VI. CONSUMED MECHANICAL POWER

Power consumption is one of the main important factors in the field of active control suspension design. In the test of the proposed model at reference of (70 mm) it can be noticed in Fig.17 that NARMA-Fuzzy technique can produce less power consumption as compared with tuned PID under some condition s of road shape and time of simulation. The same result can be proved when RMS of power is considered , Fig.18. Either before (20 sec) (the time of reflection of power behavior) or after that, the proposed model able to control the system for small overshoot and high stability. However, in the case of (Zero) reference , the presented scheme consumes more amount of power than that of other model but it appears acceptable performance of the response with respect to the range of oscillation and the ability of prediction (Figs.19 and 20).

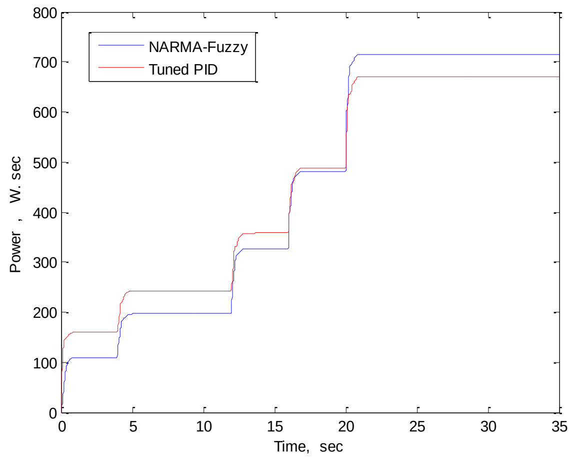


Fig.17 Power relations at reference of (70 mm).

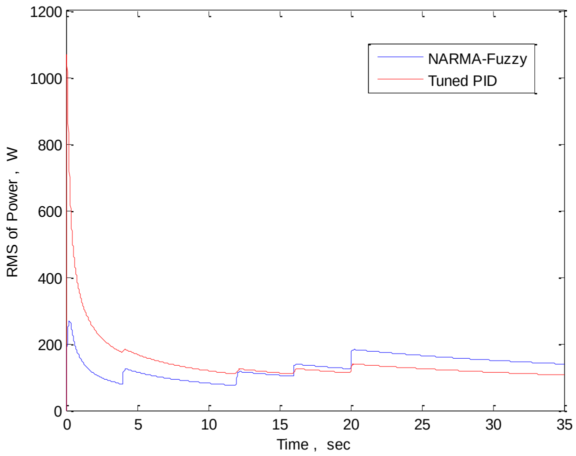


Fig.18 Relations of RMS of power at reference of (70 mm).

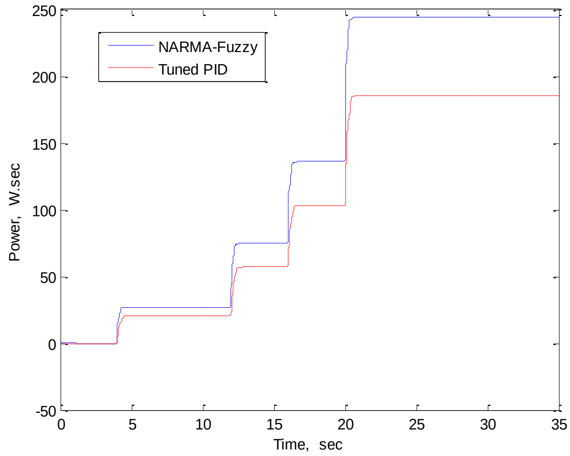


Fig.19 Power relations at reference of (Zero mm).

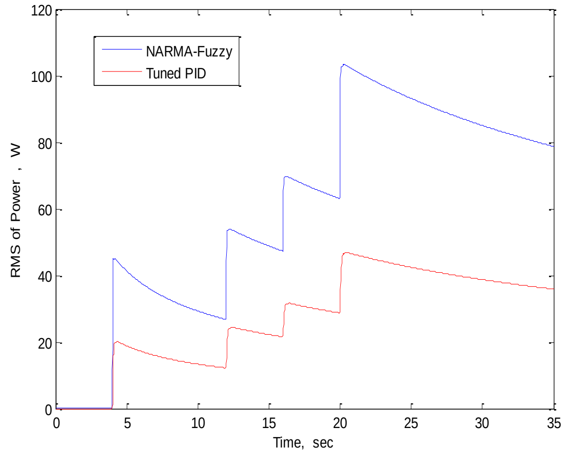


Fig.20 Relations of RMS of power at reference of (Zero mm).

VII. VIBRATION ISOLATION COMPARISON

The final goal is to illustrate the vibration of car (displacement) when a sudden change in the road disturbance takes place. The displacement of car body and wheel will be changed with a great ranges as shown in (Fig.21) and (Fig.22). However, the active suspension controller proposed in this work (NARMA-Fuzzy) will reduce the relative vibration between the car body and wheel to a very small quantities as it appear clearly in (Fig.23).

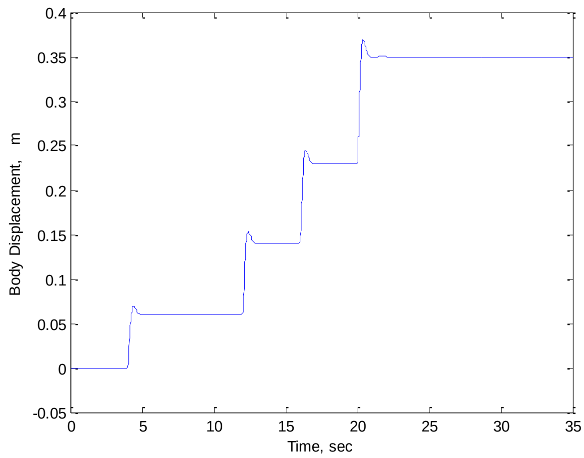


Fig.21 Car body displacement.

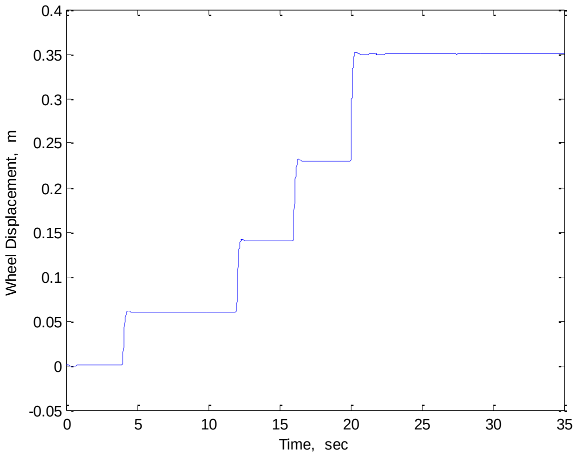


Fig.22 Wheel assembly displacement.

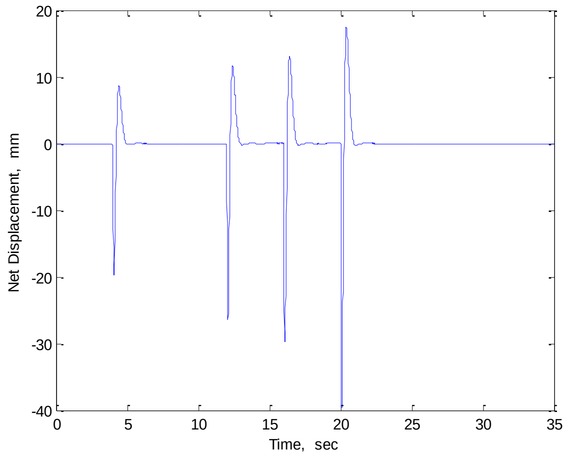


Fig.23 Net relative displacement.

VIII. CONCLUSIONS

The presented active controller for suspension system which was named as NARMA-Fuzzy has been tested at both variable and constant set-point. The result showed high efficiency and accuracy of this model. An acceptable percent overshoot can be reached with proposed model as compared with other conventional and passive schemes. NARMA-Fuzzy model can process more nonlinearity of road shapes and it may control the deflection as well as its speed and acceleration at the same time of simulation which cannot be implemented with more of other techniques. Proposed model proved that it may produce small power consumption for special cases of road variations. In the other hand, it usually need to supply the model more power against other classical schemes in order to reduce the vibration with high robustness which is the main object of suspension system designer. The result of power was calculated as the average of power and root mean square of power for more confidence where the intelligence of presented model had appeared effectively.

IX. ACKNOWLEDGMENT

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