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Improvement the Vehicle Suspension System Performance Using Fuzzy Controller

Dirman Hanafi[1*], Andrew Ho Ming Chye[1], Esmeralda C. Djamal[2], Hisyam Abdul Rahman[1], Alexander Setiawan[3], Abu Ubaidah Shamsuddin[1], Mohamad Hafis Izran Ishak[4], Ruzairi Abdul Rahim[1], Rozaimi Ghazali[5]

[1]Instrumentation and Sensing Technology (InSeT) Research Group, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Batu Pahat, 86400, Johor, MALAYSIA

[2]Department of Informatics,
Universitas Jenderal Achmad Yani, Jalan Terusan Jenderal Sudirman Cimahi 40531, INDONESIA

[3]Informatic Department, Petra Christian, University Surabaya, Jl. Siwalankerto No.121-131, Siwalankerto, Wonocolo, Kota SBY, Jawa Timur 60236, INDONESIA

[4]Process Tomography & Instrumentation Research Group (PROTOM-i), Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Johor, MALAYSIA

[5]Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Melaka, MALAYSIA

*Corresponding Author

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Abstract: An ideal car suspension system should be stiff enough for better handling while soft enough for better ride comfort factor to the passenger. Passive suspension system often have fixed shock absorber which compromise in between ride comfort and handling factors. In this paper, an active suspension system of a quarter car based on fuzzy control is developed to meet both need of ride comfort and good road handling. The suspension is assumed consist of spring and variable shock absorber. Fuzzy controller has function to control the variable shock absorber. The control structures are based on the combination of the body displacement, wheel displacement and suspension. The proposed controller system has been simulated, and is then compared with the response of passive suspension. Simulation results show that fuzzy controller based suspension system provide better ride comfort and road handling, because it decreases the vehicle body acceleration, small overshoot and settling time.

Keywords: Mathematical model, light car, passive suspension, neuro model, artificial road surface

1. Introduction

A system control is set of device or circuits that manages a larger system by receiving information and sending commands to control the larger system devices behavior [1]. Control system are analogical and mathematically accurate by nature. It is however, under certain complex condition to meet an objective, human's reasoning tend to be uncertain or imprecise, or in fuzzy condition. This uncertain input reasoning from human can't be processed by control system because computers run based on binary reasoning [2]. Fuzzy logic is a way to make machines more intelligent enabling them to reason in a fuzzy manner like humans. Fuzzy logic was proposed by Lotfy Zadeh in 1965, emerged as a tool to

**Corresponding author:dirman@uthm.edu.my*

deal with uncertain, imprecise, or qualitative decision-making problems [2,3]. Fuzzy control is result from 'try and error' experiments rather than derivation from mathematical models. As the result, linguistic implementations are much faster accomplished with fuzzy control. Fuzzy control strategies involve a large number of inputs of a scale value. Fuzzy inputs are activated only when the related condition or the reading is at certain range. In such condition, input that are not within certain range require additional fuzzy rule. As a result, the rule base structure remains understandable, leading to efficient coding and system documentation [2].

To sum up, the advantage of fuzzy controller is its aptitude to deal with nonlinearities and uncertainties. Fuzzy control can integrate control and supervision task in a user-friendly way, which it is capable of accommodating Proportional Derivative Integral (PID) control system strategies [2,3].

The aim of this project is to design a fuzzy control system to control the damping of an independent quarter car suspensions system of a full car model. Implementing a fuzzy control system into car suspension changes its characteristic into a fully active suspension which is able to manipulate its damping rate in response to variation of road conditions, thus able to achieve both optimum ride quality and good handling.

This paper has the following structure: Section 1 provides the brief overview state of the art of this research, Section 2 explains the components of the suspensions and how its mathematical model is derived, Section 3 presents the fuzzy control system principles and its block diagram, Section 4 explains the mechanism to implement the suspension model and fuzzy control system in Simulink block, in Section 5 elaborates the experimental test results of the fuzzy control system develop and analysis of results, and finally the conclusions are drawn in Section 6.

2. A Quarter Car Mathematical Model

There are 2 types of mass in an automotive suspension system, that they are important to determine the balance of the firmness of suspension setting for comfort [4] or performance. Those mass are sprung mass and un-sprung mass [517].

2.1 Sprung Mass

Almost the entire loads on the car carried by the suspension are sprung mass [5-7]. The portion of the total mass of the vehicle supported by the suspension system is called sprung mass. The sprung mass includes the weight of: body, chassis or frame, engine, gearbox, petrol tanks, passengers and cargo [5-11].

2.2 Un-sprung Mass

Un-sprung weights are all the components below the suspension [5-17]. At the lower part of the springs, therefore un-sprung mass react to roadway irregularities without damping, other than the pneumatic effect of the tyres. The rest of the mass is on the vehicle side of the springs which represent sprung weight. Disturbances and noise generated from the tyre and road are mostly filtered by the suspension system and as a result are not fully experienced by the sprung weight (passenger). The un-sprung mass includes the weight of: tyre, wheel rim, brake disk and calipers or brake drums, suspension linkages (lower control arms, upper control arms) [5-11].

2.3 Main Suspension Component

The main suspension component of a car are spring, shock absorber, rims and tyres.

Spring

Springs are the ones to carry most of the heavy loads in most suspension applications either its used in independent or dependent suspension configuration [5,7,8,10,14,18,19]. The height of the vehicle and its length of suspension stroke greatly affected by its spring rate. The force required to compress or stretch the spring is directly perpendicular to its change in length. There are generally 4 types of springs being used for automotive suspension: coil springs, leaf spring [19], torsion bars spring and air springs.

Shock Absorber

Shock absorber is a mechanical device with hydraulic fluid as the main element to resist the uncontrolled movement of the suspension [5,7,8,10,14]. It control the movement by limiting the rate of extension of the spring after the compression cycle due to bump. This process is called damping effect. To control the rate of extension of spring in suspension, the absorber convert the kinetic energy from the extension of spring into heat energy through hydraulic fluid inside it.

To summarize the role of shock absorber, the spring in the suspension controls the motion of the vehicle's un-sprung weight while then shock absorber control sprung weight from bouncing by controlling the extension of the spring [9,11,12]. Today, all modern shock absorbers are designed to be velocity sensitive. The faster then suspension move, the higher the resistance of the shock absorber. Such capability enable the shocks to respond to various road condition [20] and reduce the effect of unwanted motions when vehicle on the road such as acceleration squat, bouncing and brake dive.

Rims and Tyre

Rim is a solid wheel holding the tyre [5-17]. It is designed to be mounted at the inner edge of the tyre's belt. Rims are normally made of sheet of metal or composite alloys. Manufacturer often design the rim to be strong to with stand the harsh road punishment while being as light weight as possible to ensure lower un-sprung weight.

Tyre is part of a ring-shaped vehicle component made from rubbers to surround the rim wheel of the car. Tyres are widely used for providing better road traction on the road with its flexible surface while providing shock absorption from its flexible cushion of pneumatic effect [5,6,14-17]. Tyres consist of tread surface and containment body along then sidewalls. The thread surface provides tyre traction to grip on the road while the tyre sidewalls stores the compressed air. The vertical stiffness of a tyre increases linearly and perpendicularly with the tyre pressure.

2.4 Model of Car Suspension System with Active Damping

The following figure is a passive damping rate and a passive spring rate of car suspension system dynamics model [5,7,21].

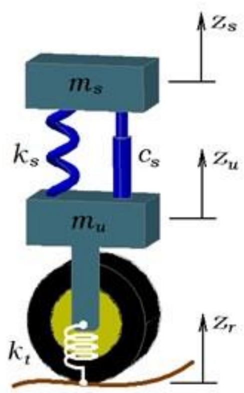

Fig. 1 - Equivalent model of an active damping suspension system

where: m_s, m_{us}, k_s, k_t, c_s, z_s, z_u and z_r are sprung weight, un-sprung weight, suspension spring rate, tyre pressure, suspension damping rate, sprung weight vertical displacement, un-sprung weight vertical displacement and road input displacement respectively.

The suspension system with active damping of a quarter car mathematical formula in this paper is derived from the suspension equivalent diagram as shown below. The suspension characteristic is assumed linear.

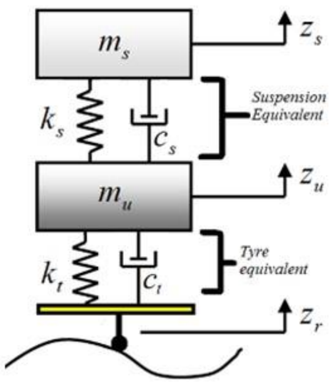

Fig. 2 - Car suspension model assume to be linear in calculation

where: C_t is the tyre sidewall stiffness.

Eq. (1) and (2) below represent the equation for sprung and un-sprung mass of the model respectively. For sprung weight equation is

$$M_s.\ddot{Z}_s = -K_s(Z_s+Z_u) - C_s(\dot{Z}_s + \dot{Z}_u) \qquad (1)$$

Equation for un-sprung weight is

$$M_u.\ddot{Z}_u = -K_s(Z_s + Z_u) - C_s(\dot{Z}_s + \dot{Z}_u) + K_t(Z_r - Z_u) + C_t(\dot{Z}_r - \dot{Z}_u) \qquad (2)$$

where:

Z_r = road input displacement, M_s = sprung weight, Z_u = un-sprung weight displacement, M_u = un-sprung weight, Z_s = sprung weight displacement, C_s = passive absorber stiffness, K_s = spring rate, C_t = tyre sidewall stiffness, K_t = tyre pressure.

If $-X = Z_s - Z_u$, and X is the suspension displacement as output variable and substitute into Eq. (2).

$$M_s.\ddot{Z}_s = K_s.(-X) + C_s.(-\dot{X})$$

$$M_u.\ddot{Z}_u = C_s.-\dot{X}+K_s.-X + K_t.(Z_r - Z_u) + C_t.(\dot{Z}_r - \dot{Z}_u)$$

$$M_u.\ddot{Z}_u = -C_s\dot{X}-K_sX + K_tZ_r - K_tZ_u + C_t\dot{Z}_r - C_t\dot{Z}_u$$

$$K_tZ_u = -M_u.\ddot{Z}_u - C_s\dot{X}-K_sX + K_tZ_r + C_t\dot{Z}_r - C_t\dot{Z}_u$$

$$Z_u = -\frac{M_u}{K_t}\ddot{Z}_u - \frac{C_s}{K_t}\dot{X} - \frac{K_s}{K_t}X + \frac{K_t}{K_t}Z_r + \frac{C_t}{K_t}\dot{Z}_r - \frac{C_t}{K_t}\dot{Z}_u$$

$$Z_u = -A_1Z_u - A_2X - A_3X + A_4Z_r + A_5Z_r - A_6Z_u \qquad (3)$$

Related to sprung weight displacement, if $X = Z_u - Z_s$ and substitute in Eq. (1)

$$M_s\ddot{Z}_s = C_sX + K_sX$$

$$M_s\ddot{Z}_s = M_sZ_s + M_sZ_s$$

$$M_s\ddot{Z}_s = M_sZ_s + M_sZ_s = C_sX + K_sX$$

$$M_s\ddot{Z}_s = -M_sZ_s - M_sZ_s + C_sX + K_sX$$

$$M_sZ_s = -M_s.\ddot{Z}_s - M_s\dot{Z}_s + C_s\dot{X} + K_sX$$

$$Z_s = -\frac{M_s}{M_s}\ddot{Z}_s - \frac{M_s}{M_s}\dot{Z}_s + \frac{\dot{C_s}}{M_s}X + \frac{K_s}{M_s}X$$

$$Z_s = -B_1\ddot{Z}_s - B_2Z_s + B_{\dot{3}}X + B_4X \qquad (4)$$

3. Fuzzy Control System

The purpose of control system is to influence the behavior of a system by manipulating an input or inputs to that system in order to follows the rule or set of rules that model how the system operates. The system can be controlled by mechanical, electrical, chemical or any combination of these [3]. The fuzzy logic controller used in this study is the Mamdani fuzzy inference system. This type has the advantage of having more ability to describe the expertise of an expert when compared to others. It is very useful among others for the following 2 things: (1) in matters that are involved with very complex system systems with its behaviors do not well understood, and (2) in situations where the solution is approximated, but fast, solution is warranted [22].

Fuzzy sets and logic are viewed as a formal mathematical theory for representation of uncertainty of linear input and output. Uncertainty is crucial for the management of real systems. For example, if a cruise control were to maintain the car’s speed of 80kmh precisely, it is not possible. Instead the cruise control system have to work within a tolerance of 5kmh whereby the speed is control to be within the range of 75kmh to 85kmh. The presence of uncertainty in real world is unavoidable when handling a complex system.

Fuzzy control system replaces the mathematical model of block diagram and replace it with another closed-loopcontrol system which is built from few number of rules that reflect a small part of the system’s linear output and input. It a process of binding them together to produce the desired outputs. To sum up, the fuzzy model has been replaced with the mathematical model, whereby the input and output of the system remained unchanged [3].

Fuzzy Block Diagram

The block diagram as shown in Fig. 3 represents the flow process of the fuzzy control system. The main objective of the suspension is to achieve the reference ride height of the vehicle. When running on the road the suspension height, (t) changes due to road irregularities. The changes in suspension height is sent to the fuzzy inference control system.
In the fuzzy system, the input will be converted into fuzzy sets via fuzzification. The fuzzy input values are then sent to the inference mechanism of fuzzy control to compare with the fuzzy rule base. The processed output of inference mechanism is then converted via de-fuzzification into analog scalar values as inputs of the shock absorber to alter then firmness and responsive of the suspension [3].

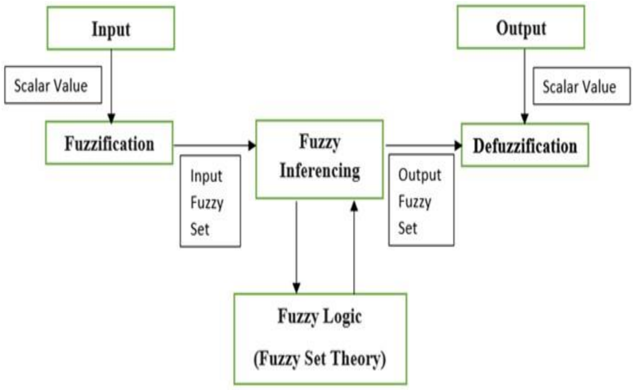

Fig. 3 - Component of fuzzy control system

4. Simulink Block Implementation

Simulink block model is built from the mathematical equation representing a quarter car suspension's sprung weight and un-sprung weight as shown in Fig. 4 and 5.

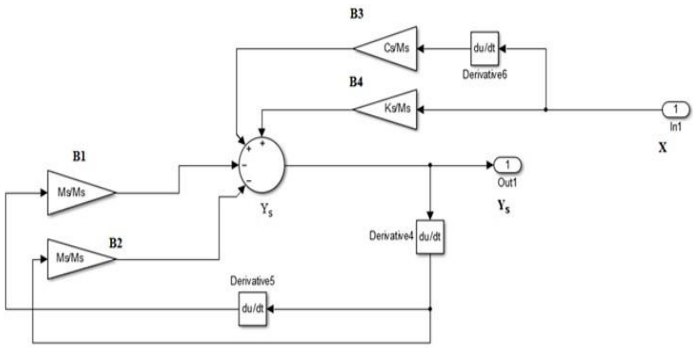

Fig. 4 - Block diagram of the Simulink for representing the sprung weight equation

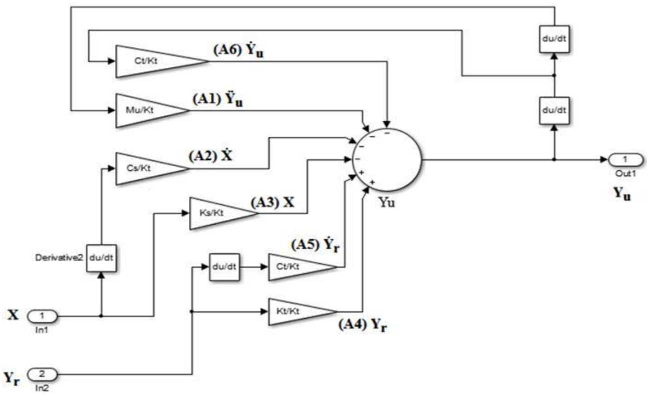

Fig. 5 - Block diagram of the Simulink for representing the un-sprung weight equation

From the equation Y = Ys − Yu , the block diagram from sprung and un-sprung weight are combine into a complete passive car suspension system as shown below.

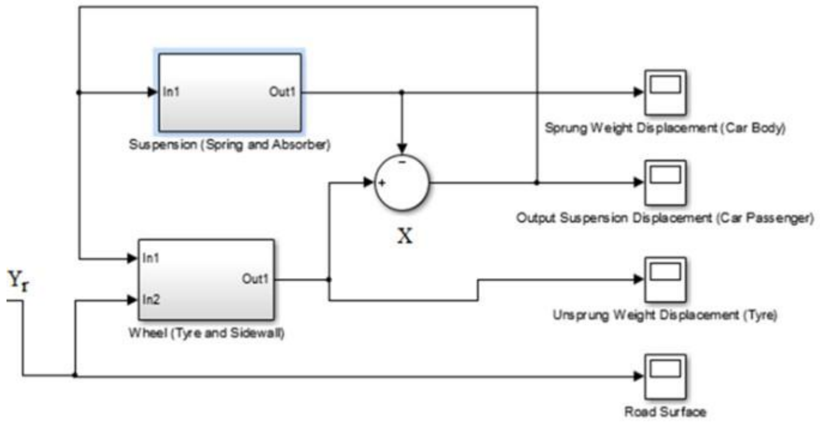

Fig. 6 - Block diagram of the Simulink for representing the whole car suspension system

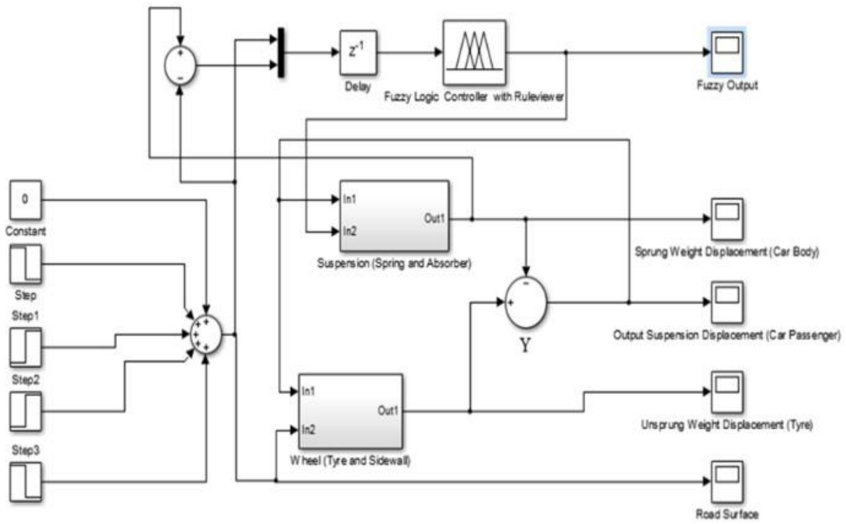

Fig. 7 - Overall block diagram representing a quarter car suspension model controlled by fuzzy controller

Currently there is no literature that states that for each membership function fuzzy logic controller is good for certain applications. Usually, in determining the type of membership function which is most suitable for an application more based on the experience of the control designer, but most are determined by approach try and error.

Therefore, in this study to obtain appropriate membership function and number of membership functions for input variables and output variables are carried out applying try and error approach. It is therefore easily understandable, but time consuming to be configured. Fig. 8, 9 and 10 show the fuzzy controller's input and output membership functions.

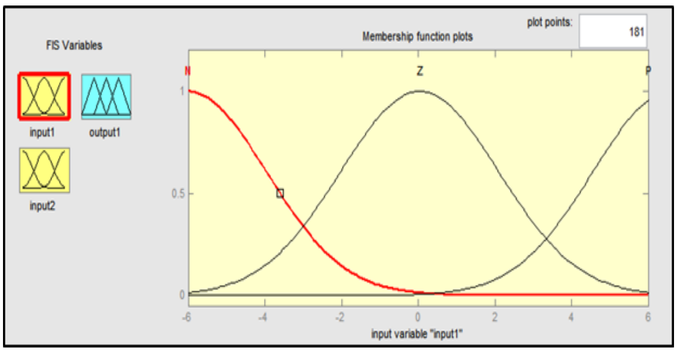

Fig. 8 - Fuzzy controller first input

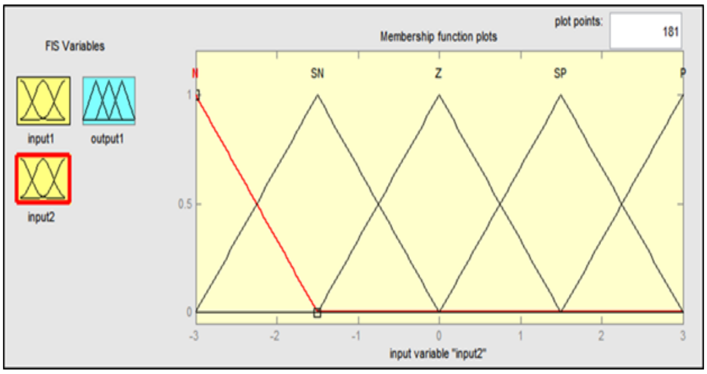

Fig. 9 - Fuzzy controller second input

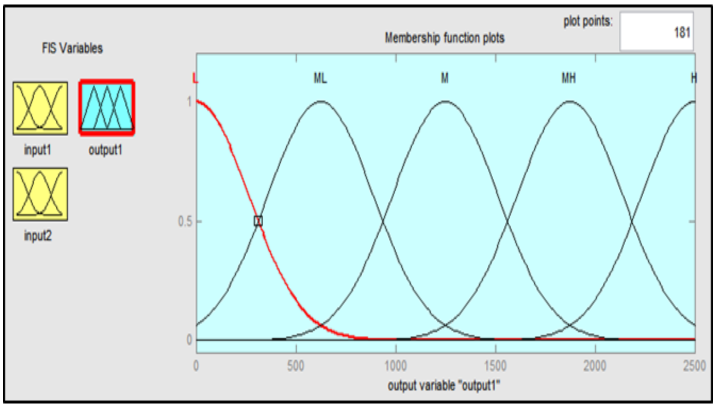

Fig. 10 - Fuzzy controller output

The fuzzy controller first input/input 1 has range from "–6 to 6" representing the input road surface, second input/input 2 has range from "–3 to 3" representing the overshoot reaction of the car suspension during impact and the output has range from "0 to 2500" is the range of strength can be set on the magnetorheological damper (shock absorber).

Rules for fuzzy controller need to be configured on how it should respond under various condition. The input 1 consist of 'Negative, Zero, Positive', input 2 consist of 'Negative, Small Negative, Zero, Small Positive, Positive' and the output memberships as shown by Fig. 10 consist of 'Low, Medium Low, Medium, Medium High, High' for strength of magnetorheological damper.

With all the fuzzy memberships, we were able to finally configure rules for the fuzzy controller. Fig. 11 and 12 show the fuzzy logic rules and the surface graph to imagine how the fuzzy works respectively.

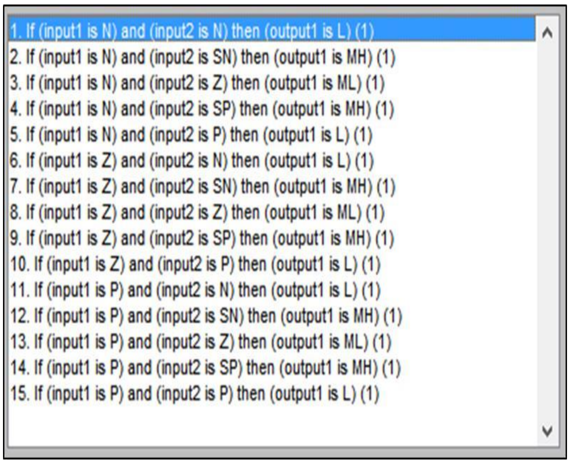
1. If (input1 is N) and (input2 is N) then (output1 is L) (1)
2. If (input1 is N) and (input2 is SN) then (output1 is MH) (1)
3. If (input1 is N) and (input2 is Z) then (output1 is ML) (1)
4. If (input1 is N) and (input2 is SP) then (output1 is MH) (1)
5. If (input1 is N) and (input2 is P) then (output1 is L) (1)
6. If (input1 is Z) and (input2 is N) then (output1 is L) (1)
7. If (input1 is Z) and (input2 is SN) then (output1 is MH) (1)
8. If (input1 is Z) and (input2 is Z) then (output1 is ML) (1)
9. If (input1 is Z) and (input2 is SP) then (output1 is MH) (1)
10. If (input1 is Z) and (input2 is P) then (output1 is L) (1)
11. If (input1 is P) and (input2 is N) then (output1 is L) (1)
12. If (input1 is P) and (input2 is SN) then (output1 is MH) (1)
13. If (input1 is P) and (input2 is Z) then (output1 is ML) (1)
14. If (input1 is P) and (input2 is SP) then (output1 is MH) (1)
15. If (input1 is P) and (input2 is P) then (output1 is L) (1)

Fig. 11 - Fuzzy controller rules

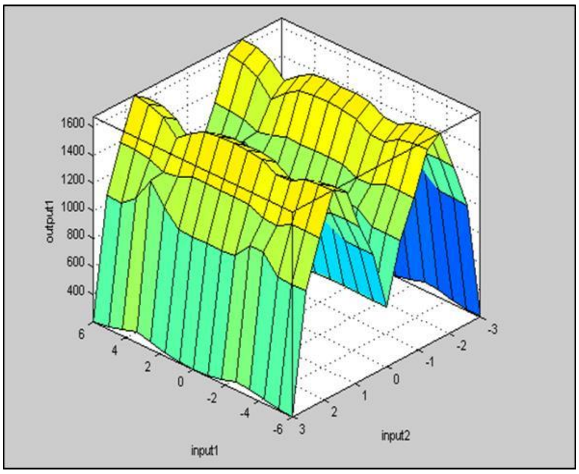

Fig. 12 - Fuzzy controller surface viewer

5. Experiment Result

Table 1 shows the spesifications of the car as an object of work.

Table 1 - Car specifications

Car component	Symbols	Obtained Quantities	Values for Math Calculation
Chassis Body Mass (Sprung Weight)	m_s	312kg	312kg
Wheel Mass (Un-sprung Weight)	m_u	50kg	50kg
Road Contact	m_r	-	-
Stiffness of Spring	K_s	5 kN/m	5 kN/m
Stiffness of Tyre	K_t	32psi	220kN/m
Stiffness of Damper (Shock Absorber)	C_s	1.5 kNs/m	1.5 kNs/m
Stiffness of Tyre Damper (Sidewall)	C_t	7 Ns/m	7 Ns/m

The simulation results of the suspension model of a quarter car for the time steps as the input signal as road condition are presented by the following figures.

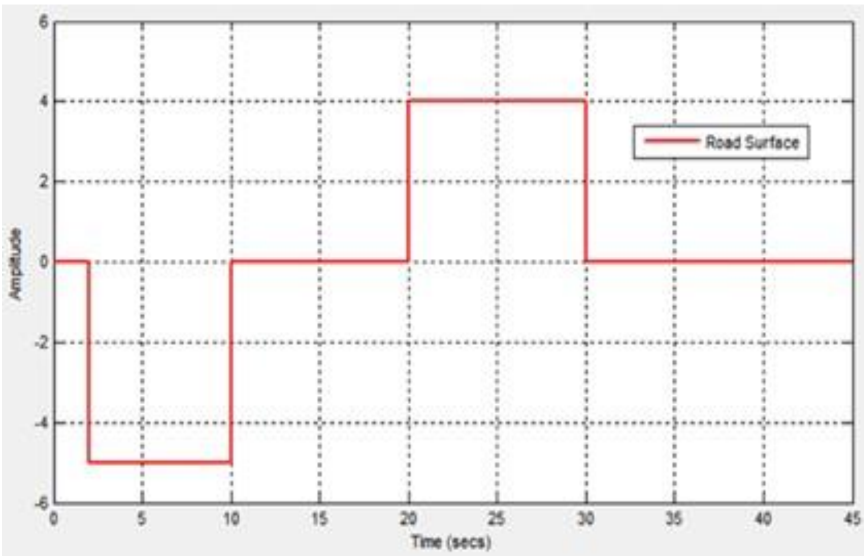

Fig. 13 - Yr, The input road surface

The input signal used in this study is shown by Fig. 13. The signal at the beginning is flat, then fall down as an indication of a hole, then returns to flat, after that it rises as an indication of bump and finally returns to flat conditions. All of that is used to show the possible form of real road surface.

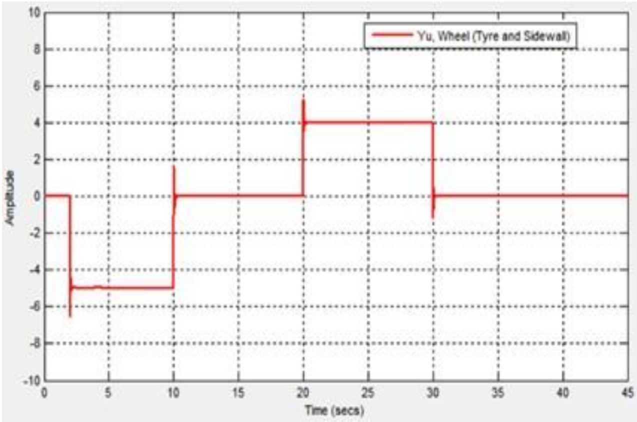

Fig.14 - Yu, Wheel (Tyre and Sidewall)

Fig. 14 above shows the response of the vehicle wheel to the input used. It show that every time the input has a change, the vehicle wheel system is not able to reduce high vibrations with appearing of a high overshoot. This is related to the characteristics of the vehicle wheel that does not has well damping properties**.**

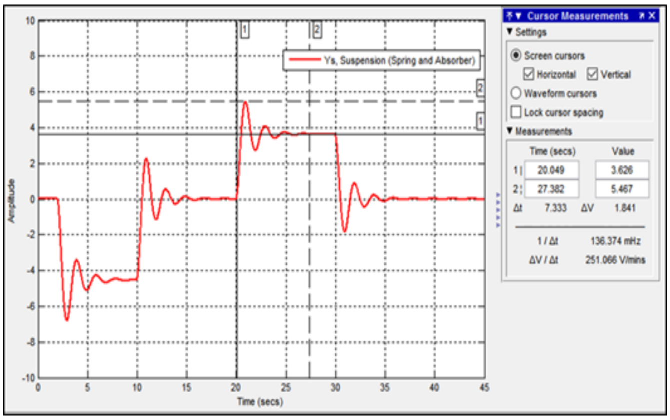

Fig. 15 - Ys, Suspension reaction without controller

From the above figure, we can deduce that the passive suspension have large overshoot amplitude value of 2 and have large settling time of 6.5 seconds. This will result the car to rock and roll uncontrollably compromising the car safety and unwanted pressure on other car components. It will cause an unpleasant experience for the vehicle's ride.

Overshoot	: 1.841/3.626 * 100 = 50% overshoot
Rise Time	: 0.5 seconds
Settling Time	: 7 seconds
Steady state error	: 0

Fig. 16 shows the response of an active suspension system under Proportional Integral Derivative (PID) controller.

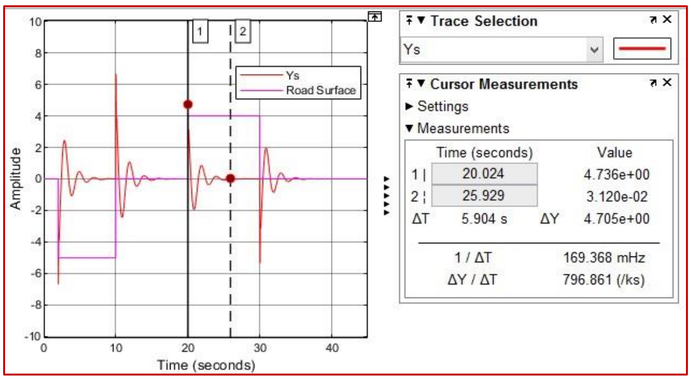

Fig. 16 - Ys, Suspension reaction with PID controller

The above figure gives an active suspension system response under PID control as a controller. The highest overshoot is existed at 20.04 sec with value is 5.355. The control parameters produced are as below:

Overshoot	: 1.355/4.000 * 100 = 33.88% overshoot
Rise Time	: 20.18 seconds
Settling Time	: 0 seconds
Steady state error	: 4

Based on results elaborate previous shows that PID control is not able to control the system because it gives worst performance. This is due to the high nonlinearities and the complexity of the system.

Next figure presents an active suspension system under fuzzy logic control as a controller of the system.

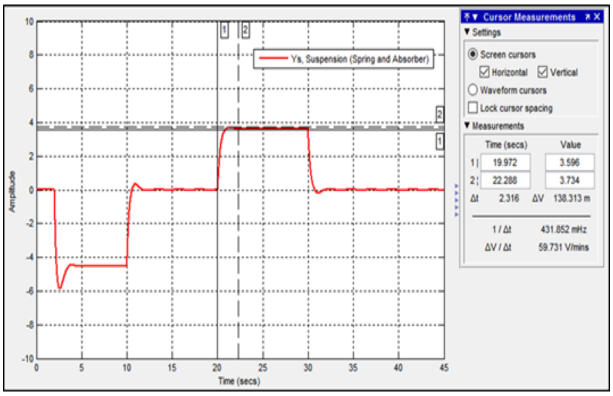

Fig. 17 - Ys, Suspension reaction with fuzzy controller

From the output graph of suspension reaction, the maximum overshoot of the suspension has been greatly reduced to 1.5 as maximum and 0.1 as minimum overshoot. The suspension also has reduced the settling time to only 2.3 seconds.

Overshoot	: 0.1/3.626 * 100 = 2.75% overshoot
Rise Time	: 0.5 seconds
Settling Time	: 2.3 seconds
Steady state error	: 0

6. Conclusion

This project has been successfully developed. The suspension system of a quarter car simulation with fuzzy control system shows a shorter settling time compare to passive suspension system and PID control system. Based on the results obtained from the simulation, it can be concluded that fuzzy control is very effective and can be used to achieve both ride comfort and good handling. Fuzzy control system are gaining popularity among consumers, and industries. They are able to handle instable conditions whereby the input signals are close but precise. Fuzzy uses descriptive rules to relate input information to output actions, thus eliminating the need of complex mathematic calculation. This advantage greatly help engineers to focus on the function of the system and not on mathematics. With successful implementation, fuzzy is not only able to control the behavior of car suspension but also flexible tool to pervade other fields of system.

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