Fuzzy Logic Controller for Half Car Active Suspension System

A.A. Basari[1], N.A.A. Nawir[1], K.A. Mohamad[2], X.Y. Ng[1], and A.M. Khafe[1]
[1]Centre for Telecommunication Research & Innovation (CeTRI), Faculty of Electronic and Computer Engineering, Universiti Teknikal Malaysia Melaka (UTeM), 76100 Durian Tunggal, Melaka, Malaysia
[2]Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, Malaysia
amat@utem.edu.my

***Abstract*— This work presents the MATLAB/Simulink simulation results of half car active suspension system controlled by the fuzzy logic controller. The half car model consists of one front and rear wheel. Firstly, a mathematical model of the suspension system is developed. Based on the developed mathematical model, the fuzzy logic controller for the system is designed. The input to the controller is the vertical displacement and velocity of the front body of the vehicle. The membership function of these two variables is adjusted accordingly so that the output, i.e., the car body acceleration, the deflection of the wheels and other output are better than that of the passive suspension system. The results clearly show that all of the active suspension system output has improved when compared to that of the passive system.**

***Index Terms*— half car model, active suspension system, passive suspension system, fuzzy logic.**

I. INTRODUCTION

Stability and ride comfort of vehicles while running on the road is determined by many factors. One of the important systems that determine the stability of the vehicle is suspension system. The typical suspension system consists of shock absorber and coil spring. Combination of these two components in the system produces the desired comfort to the passenger in the vehicles. Suspension system can be classified into three main categories namely passive suspension, semi-active suspension, and active suspension system. For the configuration of the semi-active suspension system, its damping coefficient of the shock absorber is the one that can be controlled. In contrast with the semi-active suspension system, the fully active suspension system is configured to form a third control element which designed to dissipate energy that comes into the system.

The main purpose of the active suspension system is to increase the performance of suspension system by giving better ride comfort and stability. The design of active suspension system can be classified into the quarter, half and full model [1-2]. There are various types of control schemes that have been evaluated in controlling the system. The choice of the control schemes is based on the model of the suspension system that evaluated; linear, or nonlinear model. The linear model of active suspension system models were evaluated in the early years of research in this field. Amongst the popular control schemes introduced at the time are LQR controller, PID controller and Pole Placement controller [3-5]. The model used in these papers is quarter car model. The target was to enhance the performance of the vehicles in dissipating the energy that transmitted from the road surface. For the nonlinear model, amongst the control schemes that performed well are PI sliding mode controller, backstepping controller, and nonlinear optimal control scheme [1-2, 6]. In these papers, the researchers have considered the nonlinearity of the suspension model in their mathematical derivation.

The fuzzy logic controller is one of the control schemes that capable to deal with nonlinear systems. This is due to the fact that it possesses the nonlinear mapping capabilities which not require one to have an analytical model for controlling the system [7-9]. Its application in many systems such as magnetic bearing system [10], mobile robot [11], solar PV system [12] and power system [13] is due to the advantages that it has. The most well-known fuzzy control model can be divided into two; i.e., Mamdani model and Takagi-Sugeno model. In the previous works, [14] proposed the use of mamdani model for controlling a quarter car suspension system while [15] utilised the Takagi-Sugeno approach. The main difference of both approaches is at the output side where the output of the Mamdani approach is in the form of a fuzzy set, while the Takagi-Sugeno approach produces an output that is in the form of a constant value [16]. Work on the application of fuzzy logic controller in controlling the quarter car active suspension system is widely available in the literature [17-21]. It shows that the quarter car model is well controlled by this method.

This paper presents the modelling of half car active suspension system using a fuzzy logic controller. As for this work, focus on the application of Takagi-Sugeno approach will be discussed. The modeling of the fuzzy logic controller for the system is presented. Next, analysis on the time domain performance of the system was done using MATLAB/Simulink software. Its performance was also compared with the passive suspension system of the same model of vehicle.

II. MODELING OF HALF CAR SUSPENSION SYSTEM

Half car suspension system which consists of one front and the rear wheel is shown in Figure 1. The system is governed by equation (1).

$$M\ddot{X} + S\dot{X} + TX = Df + Ew \quad (1)$$

In this equation, X, f, and w represent the state vector, active control vector and excitation vector of the system. The elements of the vector are stated below.

$$X = [x_{bf} \quad x_{wf} \quad x_{br} \quad x_{wr}]^T, f = \begin{bmatrix} f_f \\ f_r \end{bmatrix}$$

$$w = [\dot{w}_f \quad w_f \quad \dot{w}_r \quad w_r]^T$$

For the matrices of M, S, T, D and E they are given as follows:

$$M = \begin{bmatrix} L_r m_b/L & 0 & L_f m_b/L & 0 \\ I_b/L & 0 & -I_b/L & 0 \\ 0 & m_{wf} & 0 & 0 \\ 0 & 0 & 0 & m_{wr} \end{bmatrix}$$

$$S = \begin{bmatrix} c_{bf} & -c_{bf} & c_{br} & -c_{br} \\ L_f c_{bf} & -L_f c_{bf} & -L_r c_{br} & L_r c_{br} \\ -c_{bf} & c_{bf} & 0 & 0 \\ 0 & 0 & c_{br} & -c_{br} \end{bmatrix}$$

$$T = \begin{bmatrix} k_{bf} & -k_{bf} & k_{br} & -k_{br} \\ L_f k_{bf} & -L_f k_{bf} & -L_r k_{br} & L_r k_{br} \\ -k_{bf} & k_{bf} + k_{wf} & 0 & 0 \\ 0 & 0 & -k_{br} & k_{br} + k_{wr} \end{bmatrix}$$

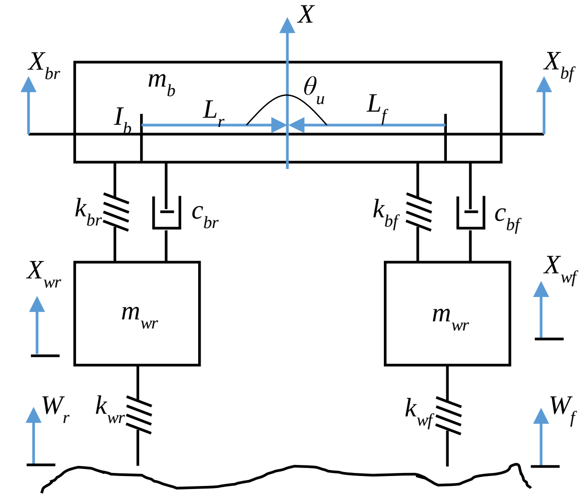

Figure 1: Model of the half-car active suspension system.

By defining the N state variables for the system as $x_i = X$ and

$$x_{i+N/2} = \dot{X}$$

where i = 1, 2, 3,…, N/2, equation (1) then can be rewritten in a state space form as follows:

$$\dot{x}(t) = Ax(t) + B_p z(t) \tag{2}$$

where

$$A = \begin{bmatrix} 0_{\frac{N}{2}\times\frac{N}{2}} & I_{\frac{N}{2}\times\frac{N}{2}} \\ A_{p1} & A_{p2} \end{bmatrix} \text{ and } B = \begin{bmatrix} 0_{\frac{N}{2}} \\ M^{-1}E \end{bmatrix}$$

$$A_{p1} = -M^{-1}T, A_{p2} = -M^{-1}S$$

The state variables were selected and defined as follows:

$x_1 = x_{bf}$
$x_2 = x_{wf}, x_3 = x_{br} \quad x_4 = x_{wr}$
$x_5 = \dot{x}_{bf} \quad x_6 = \dot{x}_{wf} \; x_7 = \dot{x}_{br}$ and $x_8 = \dot{x}_{wr}$

The analysis with rewriting equation (2) into the following form includes the disturbance function to the state equation.

$$\dot{x}(t) = Ax(t) + Bu(t) + f(t) \tag{3}$$

where $x(t) \in \Re^n$ is the vector that represents the state variables, $f(t)$ is the disturbance input from the road surface and $u(t) \in \Re^m$ represents the control input signal from the fuzzy logic controller. Lastly, the $B = \begin{bmatrix} 0_{\frac{N}{2}} \\ M^{-1}D \end{bmatrix}$.

The variables of the suspension system are summarized in Table 1.

III. Fuzzy Logic Controller Design

Design of fuzzy logic controller involves three main procedures namely fuzzification procedure, rule base determination procedure and lastly the defuzzification procedure. As mentioned earlier in the above, for the suspension system developed in this work, the front body vertical displacement and velocity signal were used as the regulated input signal. Therefore, the membership function of the two signal was determined, and it is shown in Figs. 2 and 3. Active control signal f_f and f_r are the output of the fuzzy controller, and their membership function is shown in Fig. 4.

Table 1
Variable of the suspension system

I_b	mass moment of inertia
m_b	mass of the vehicle body
m_{wf} , m_{wr}	wheel's mass (front and rear)
x_{bf} , x_{br}	body vehicle's vertical displacement (front and rear)
x_{wf} , x_{wr}	wheel's vertical displacement (front and rear)
W_f , W_r	irregular excitations from the road surfaces
L_f , L_r	distances from the front and rear suspension locations
θ_u	rotary angle.
f_f , f_r	control signal (front and rear)

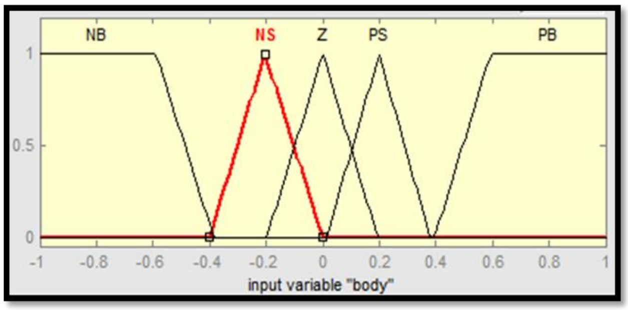

Figure 2: Membership function of body displacement

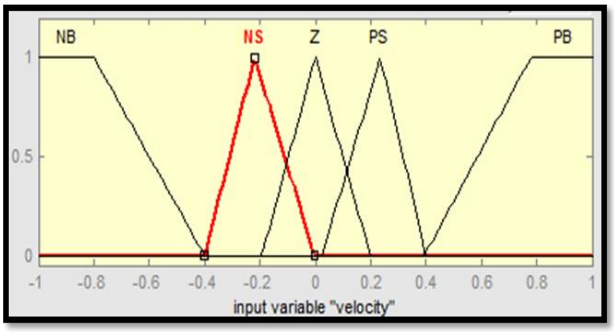

Figure 3: Membership function of body velocity

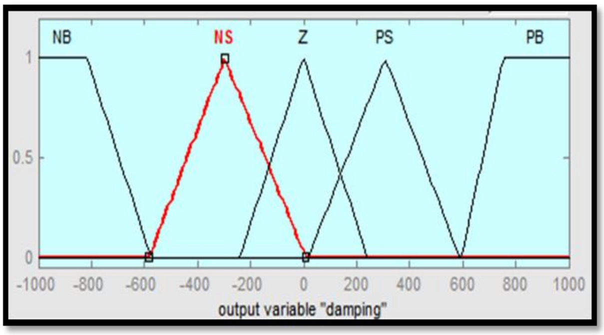

Figure 4: Membership function of the desired actuator force

The abbreviations used in the membership function are translated as follows: NB → negative big, PB → positive big, NS → negative small, PS → positive small and Z → zero. The rule base was determined according to the knowledge and experience in using the fuzzy logic controller. The target of the rule base is to minimize the vehicle body acceleration and subsequently the body displacement of the vehicle.

The rule bases of the fuzzy logic controller from Table 2 can be translated into the ordinary language as follows:

Rule no. 5: IF velocity of the body is negative big AND displacement of the body is negative big THEN the actuator force is set to be positive big.

Rule no. 10: IF velocity of the body is negative small AND displacement of the body is negative big THEN the actuator force is set to be positive big.

Rule no. 20: IF velocity of the body is positive small AND displacement of the body is negative big THEN the actuator force is negative small.

The fuzzy logic controller produces output in a fuzzy set. To obtain the signal in non-fuzzy value, defuzzification procedure is needed. The defuzzification procedure called as "center of gravity (COG)" is used for the conversion. The equation that governed the conversion is given by equation (4). $\mu_D(f)$ is the membership function.

$$f = \frac{\int f * \mu_D(f) df}{\int \mu_D(f) df} \quad (4)$$

IV. SIMULATION AND DISCUSSION

To evaluate the designed suspension system performance, MATLAB/Simulink software was used to simulate it. The numerical values of the suspension system listed in Table 3 were used [2]. A performance comparison was carried out with the passive suspension system.

Table 2
The rule base

No.	Velocity of the body	Displacement of the body	Actuator force
Rule no. 1	NB	PB	NB
Rule no. 2	NB	PS	NS
Rule no. 3	NB	Z	Z
Rule no. 4	NB	NS	PS
Rule no. 5	NB	NB	PB
Rule no. 6	NS	PB	NS
Rule no. 7	NS	PS	NS
Rule no. 8	NS	Z	PS
Rule no. 9	NS	NS	PS
Rule no. 10	NS	NB	PB
Rule no. 11	Z	PB	NB
Rule no. 12	Z	PS	NS
Rule no. 13	Z	Z	Z
Rule no. 14	Z	NS	Z
Rule no. 15	Z	NB	PS
Rule no. 16	PS	PB	NS
Rule no. 17	PS	PS	NS
Rule no. 18	PS	Z	NS
Rule no. 19	PS	NS	NS
Rule no. 20	PS	NB	NS
Rule no. 21	PB	PB	NB
Rule no. 22	PB	PS	NS
Rule no. 23	PB	Z	NS
Rule no. 24	PB	NS	NS
Rule no. 25	PB	NB	NS

Table 3
Vehicle parameters

Car body, m_b	575 Kg
Centroidal moment of inertia for the car body, I_b	769 Kg/m^2
Front wheel mass, m_{wf}	60 Kg
Rear wheel mass, m_{wr}	60 Kg
Front spring coefficient, k_{bf}	1682 N/m
Rear spring coefficient, k_{br}	16812 Nm
Front tire spring coefficient, k_{wf}	190000 N/m
Rear tire spring coefficient, k_{wr}	190000 N/m
Front damping coefficient, C_{bf}	1000 N/m
Rear damping coefficient, C_{br}	1000 N/m

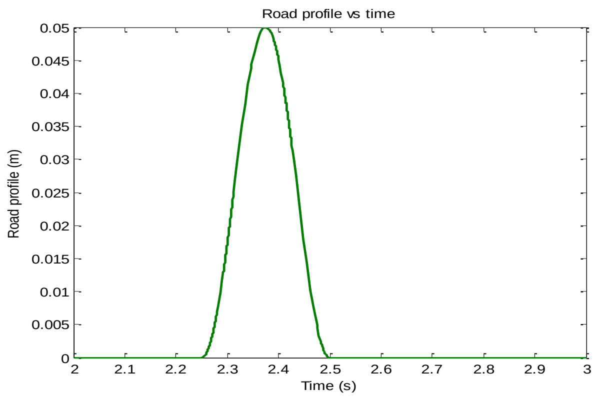

Figure 5: Road profile (the disturbance into the system)

The disturbance to the system was designed as a single road bump with a height of 5cm. The mathematical equation of the bump is given by equation (5). Figure 5 shows the road profile.

$$w(t) = \begin{cases} \dfrac{a - a\cos 8\pi t}{2} & 2.25 \leq t \leq 2.5 \\ 0 & \text{elsewhere} \end{cases} \quad (5)$$

Besides the stability, ride comfort is one of the parameters that was observed, i.e., from the acceleration and displacement of the car body while the road handling of the vehicle was observed through the wheel (front and rear) deflection. There are 4 parameters that were observed; the wheel deflection, the suspension travel, the car body acceleration (and displacement) and the forces. The simulation results of the mentioned parameters are shown in Figures. 6-9.

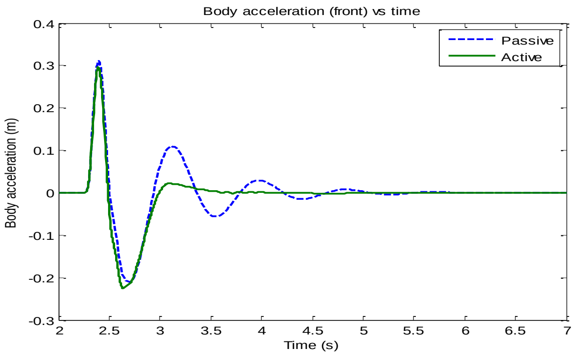

Figure 6(a): Body displacement (front)

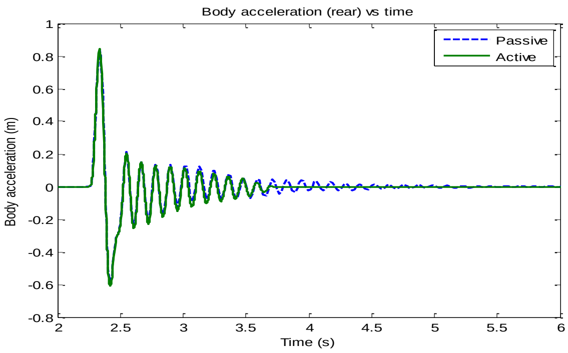

Figure 6(b): Body displacement (rear)

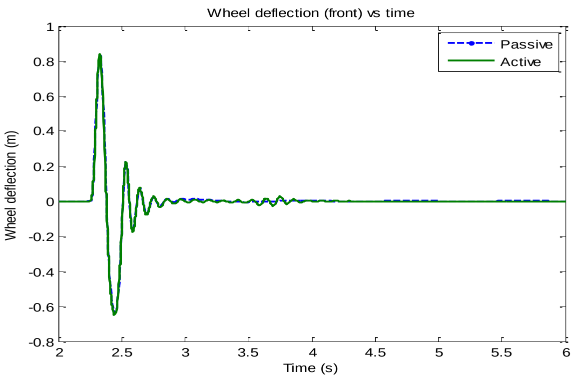

Figure 7(a): Wheel deflection (front)

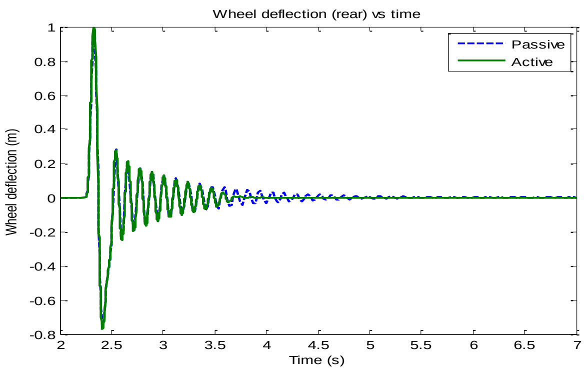

Figure 7(b): Wheel deflection (rear)

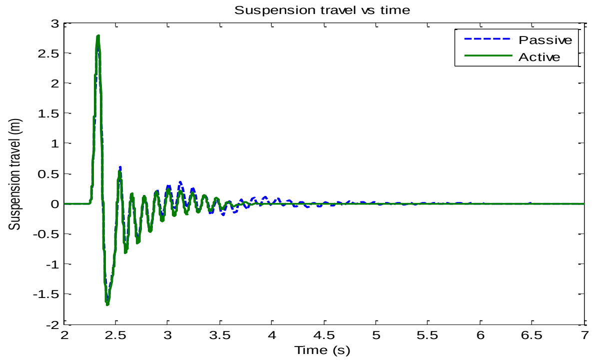

Figure 8: Suspension travel

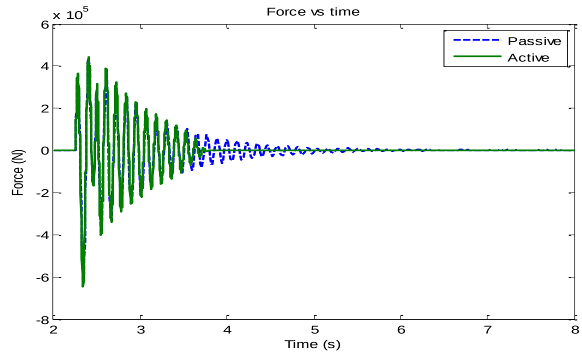

Figure 9: Force transferred to the passenger

Figures 6(a) and (b) show the displacement of the car body while Figures 7(a) and (b) shows the wheel deflection when the vehicle is going through the road bump. It is clear from these figures that performance of the active suspension system is much better when compared to the typical passive suspension system. This conclusion can be made by referring to the settling time taken by the active suspension system is much shorter than that of the passive system.

Figure 8 illustrates the results of suspension travel of the suspension system. It gives us a clear picture of the relative motion of the sprung and unsprung masses (car body and the wheels). In Figure 9, the response of the forces that transferred to the passenger is shown. For good ride quality, the forces transferred to the passenger has to be at very low level. From this graph, even though the magnitude of the forces transferred is almost same for both system, it shows to us that the active system is capable of cutting off the forces faster than the passive suspension system.

Although the results show a better performance for the active suspension system, something that can be observed is that the amplitude of the body displacement and wheels deflection are still relatively high. Further consideration of the membership function of the fuzzy logic controller maybe can help to reduce the amplitude. This is the next task in the future that planned to be taken.

V. CONCLUSION

The performances of the active suspension system of the half-car model with Fuzzy Logic Controller as the control scheme has been evaluated. The overall performance shows that the active suspension system with fuzzy logic controller gives better result in terms of the settling time.

Further investigation on the method to reduce the magnitude of the displacement and the wheel deflection is planned in the future.

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