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Active Vibration Control of Automotive Suspension System using Fuzzy Logic Algorithm

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ABSTRACT:

This study details an efficient fuzzy logic controller (FLC) to improve the performance of active automotive suspension system. A comparison between passive and FLC active suspensions is performed. A mathematical model of automotive active suspension has six degrees of freedom and two input forces generated by two separate actuators are solved using Matlab Simulink. In order to evaluate the effectiveness of the proposed controller under random road disturbance, several performance criteria are assessed based on the dynamic response of the half automotive suspension system. Simulation results of the active suspension system based on the fuzzy logic clearly have been provided to illustrate the effectiveness of the FLC under different road conditions and confirmed that fuzzy logic is very effective for enhancing ride comfort and stability of the vehicle.

KEYWORDS:

Passenger comfort; Active suspension; Fuzzy logic controller; Half car model

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1. Introduction

The comfort of the passenger and vehicle handling remains one of the most important topics that have held the researchers over the past decades in the automotive industry. Both of them are influenced by the characteristics of suspension system. The suspension system is designed to enhance the ride comfort as well as vehicle handling and stability. The suspension systems can be categorised into passive, active and semi- active systems. The passive suspension system consists of spring and oil damper (traditional system) that is quite simple, reliable and inexpensive. Nevertheless, its overall performance obstacles are inevitable. The design of suspension systems using passive components always includes a trade-off between the conflicting criteria characterizing the passenger comfort and vehicle handling. Meanwhile, the active and semi-active suspensions are implemented with sensors, controllers, actuators and a data processing unit, make it probable to apply extra suspension forces on demand to reduce the conflict between comfort, handling and safety [1].

Several different methods of control techniques were used to achieve the basic objectives of the active suspension system with passenger comfort, handling and stability of the vehicle. These methods include H_∞ controller [1], mixed H_∞/H2 controller [2], adaptive controller [3], nonlinear back stepping controller [4], fractional order controller based on evolutionary algorithm [5], genetic algorithm and neural network control [6]. Additionally, linear quadratic regulator (LQR) controller [7], neural network based feedback linearization controller [8], optimal preview controller [9], sliding mode controller [10], and PID controller [11]. All the developed control strategies based on a quarter car, half-car model and full-car model have been proposed. Fuzzy logic algorithm [12] has been used greatly and very fast in all industrial fields including automotive field. Some applications of fuzzy logic algorithm include anti-locking brake system [13] and electric power steering [14] as well as engine management [15]. The use of the fuzzy logic method for the control of a continuously damping automotive suspension system, was proposed to decrease the body acceleration caused by the car body [16] and to decrease the deflection of chassis and wheels when traversing on rough road surfaces and pavement points [17]. In order to introduce a more accurate damping the magnetorheological dampers were used [18]. A numerical model of a 7-DOF suspension with vehicle semi-active suspension fuzzy controller system was implemented by [19-21]. The simulation outcomes had shown that the developed fuzzy controller improves the ride comfort and vehicle handling without forfeiting the safety. The performance was enhanced using fuzzy-PID control with electro-hydrostatic actuator [22].

The application of fuzzy-PID under road conditions with excitations of different frequencies is very effectual. Fuzzy-PID control strategy gives a far better robustness performance than the traditional PID control. The adaptive fuzzy logic controller (FLC) was presented by [23-24], to investigate the improvement of vehicle stability, handling, and to reduce the effect of different road excitations. The outcomes of simulation revealed that the proposed adaptive FLC has superior ride comfort and vehicle handling in comparison with the passive system. PID controller with self-tunable fuzzy inference system was provided [25], to improve the comfort and vehicle handling under different road conditions. The adaptive fuzzy sliding mode control was implemented [26] to enhance the presence of parameter uncertainties and external disturbances. In this research, a half vehicle model with 6 degrees of freedom (6-DoF) was developed [27], to work in comparison between the passive and active suspensions, which are used with FLC algorithms. The mathematical model is established using MATLAB/Simulink software. The use of FLC technique in half car suspension model is the core contribution of this paper. Control performance criteria are evaluated in time domain with the view of quantifying the efficiency of active suspension compared with passive suspension.

2. 6-DoF dynamic model

The developed dynamic model as shown in Fig. 1 contains 6-DoF presenting the general equations of motion for half car model. The equations of motion of the model using Newton-Euler technique and considered parameters as per Table 1[28] are detailed as follows:

$$\begin{aligned}\ddot{x} = &-\frac{1}{m}\left(k_1+k_2+k_{p1}+k_{p2}\right)x \\ &-\frac{1}{m}\left(k_1b_1-k_2b_2+k_{p1}d_1-k_{p2}d_2\right)\theta \\ &+\frac{k_{p1}}{m}x_{p1}+\frac{k_{p2}}{m}x_{p2}+\frac{k_1}{m}x_{t1}+\frac{k_2}{m}x_{t2} \\ &+\frac{c_{p1}}{m}\dot{x}_{p1}+\frac{c_{p2}}{m}\dot{x}_{p2}+\frac{c_1}{m}\dot{x}_{t1}+\frac{c_2}{m}\dot{x}_{t2} \\ &-\frac{1}{m}\left(c_1+c_2+k_{p1}+k_{p2}\right)\dot{x} \\ &-\frac{1}{m}\begin{pmatrix}c_1b_1-c_2b_2\\+c_{p1}d_1-c_{p2}d_2\end{pmatrix}\dot{\theta}+\frac{F_{a1}+F_{a2}}{m}\end{aligned} \tag{1}$$

$$\begin{aligned}\ddot{\theta} = &-\frac{1}{I_P}\left(k_1b_1-k_2b_2+k_{p1}d_1-k_{p2}d_2\right)x \\ &-\frac{1}{I_P}\left(k_1b_1^2-k_2b_2^2+k_{p1}d_1^2+k_{p2}d_2^2\right)\theta \\ &-\frac{k_{p1}d_1}{I_P}x_{p1}+\frac{k_{p2}d_2}{I_P}x_{p2}-\frac{k_1b_1}{I_P}x_{t1} \\ &+\frac{k_2b_2}{I_P}x_{t2}-\frac{1}{I_P}\begin{pmatrix}c_1b_1-c_2b_2+c_{p1}d_1\\-c_{p2}d_2\end{pmatrix}\dot{x} \\ &-\frac{1}{I_P}\left(c_1b_1^2-c_2b_2^2+c_{p1}d_1^2+c_{p2}d_2^2\right)\dot{\theta} \\ &-\frac{c_{p1}}{I_P}\dot{x}_{p1}+\frac{c_{p2}d_2}{I_P}\dot{x}_{p2}-\frac{c_1b_1}{I_P}\dot{x}_{t1} \\ &+\frac{c_2b_2}{I_P}\dot{x}_{t2}+\frac{1}{I_P}\left(F_{a1}b_1-F_{a2}b_2\right)\end{aligned} \tag{2}$$

$$\begin{aligned}\ddot{x}_{p1} = &\frac{1}{m_{p1}}\left(k_{p1}x+k_{p1}d_1\theta-k_{p1}x_{p1}\right) \\ &+\frac{1}{m_{p1}}\left(c_{p1}\dot{x}+c_{p1}d_1\dot{\theta}-c_{p1}\dot{x}_{p1}\right)\end{aligned} \tag{3}$$

$$\begin{aligned}\ddot{x}_{p2} = &\frac{1}{m_{p2}}\left(k_{p2}x-k_{p2}d_2\theta-k_{p2}x_{p2}\right) \\ &+\frac{1}{m_{p2}}\left(c_{p2}\dot{x}-c_{p2}d_2\dot{\theta}-c_{p2}\dot{x}_{p2}\right)\end{aligned} \tag{4}$$

$$\begin{aligned}\ddot{x}_{t1} = &\frac{1}{m_{t1}}\begin{pmatrix}k_1x-k_1b_1\theta-\left(k_1+k_{t1}\right)x_{t1}\\+k_{t1}y_1-F_{a1}\end{pmatrix} \\ &+\frac{1}{m_{t1}}\left(c_1\dot{x}-c_1b_1\dot{\theta}-\left(c_1+c_{t1}\right)\dot{x}_{t1}+c_{t1}\dot{y}_1\right)\end{aligned} \tag{5}$$

$$\begin{aligned}\ddot{x}_{t2} = &\frac{1}{m_{t2}}\begin{pmatrix}k_2x-k_2b_2\theta-\left(k_2+k_{t2}\right)x_{t2}\\+k_{t2}y_2-F_{a2}\end{pmatrix} \\ &+\frac{1}{m_{t2}}\left(c_2\dot{x}-c_2b_2\dot{\theta}-\left(c_2+c_{t2}\right)\dot{x}_{t2}+c_{t2}\dot{y}_2\right)\end{aligned} \tag{6}$$

where, y_1 and y_2 are the front and rear road excitation, F_{a1} and F_{a2} are the front and rear active control forces, x_{p1} and x_{p2} are the driver and passenger displacement, $\ddot{x}_{t1}$ *and* $\ddot{x}_{t2}$ are the front and rear tire acceleration, $\ddot{x}_{p1}$ *and* $\ddot{x}_{p2}$ are the driver and passenger acceleration and θ *and* $\dot{\theta}$ are the pitch motion and pitch acceleration.

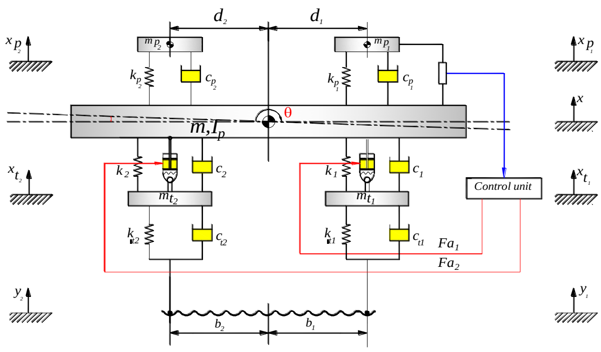

Fig. 1: 6-DoF half car model of an active suspension system

Table 1: Parameters of the half car suspension model [28]

Parameter	Description	Unit	Value
I_p	Body inertia	kg m^2	3443.05
m_{p1}	Driver mass	kg	75
m_{t1}	Front axle mass	kg	87.17
k_1	Front main stiffness	N/m	66824.2
k_2	Rear main stiffness	N/m	18615.0
kp_1	Front seat stiffness	N/m	14000
kp_2	Rear seat stiffness	N/m	14000
kt_1	Front tire stiffness	N/m	101115
kt_2	Rear seat stiffness	N/m	101115
b_1	Dimension	m	1.271
b_2	Dimension	m	0.481
m	Body mass	kg	17994.4
m_{p2}	Passenger mass	kg	14
m_{t2}	Rear axle mass	kg	140
c_1	Front main damping	Ns/m	1190
c_2	Rear main damping	Ns/m	1000
cp_1	Front seat damping	Ns/m	50.2
cp_2	Rear seat damping	Ns/m	62.1
ct_1	Rear main damping	Ns/m	14.6
ct_2	Rear tire damping	Ns/m	14.6
b_2	Dimension	Ns/m	1.713
d_2	Dimension	Ns/m	1.313

3. Random road profile

The random road input as in [29]was used as follows:

$$\dot{x}_r + \rho V x_r = V W_n \tag{7}$$

Where W_n white noise with the intensity is $2\sigma^2\rho V$, ρ is the road irregularity parameter. σ^2 is the co-variance of road irregularity. For the random road input, the road surface irregularity values are selected as (ρ=0.45 m^{-1} and σ^2 = 300 mm^2) supposing that the vehicle runs on the paved road with the forward speed V = 20m/s [29]. The road input disturbance excitation is shown in Fig. 2.

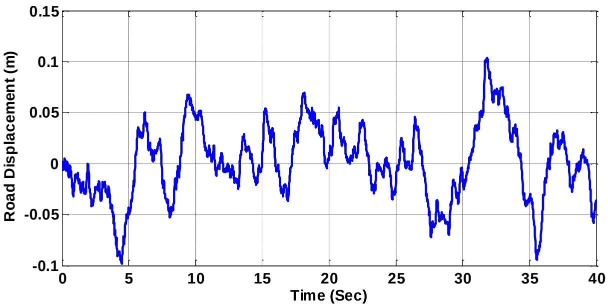

Fig. 2: Road profile with time history

4. Fuzzy logic controller

FLC is very appropriate in nonlinear systems. The main limitation in FLC is the lack of systematic procedure for design in addition to the lack of completeness of the rule base [30]. Fig. 3 shows the FLC construction with fuzzification process, fuzzy processing and de-fuzzification process. A passive and an active with fuzzy control systems are used distinctly to 6-DoF system l. Two control forces are applied to the system for smothering the vehicle vibrations. These control forces are F_{a1} and F_{a2} as presented in Fig. 1 for controlling the bounce and pitch motions of the vehicle. FLC system for the 6-DoF system uses the errors of seat travel distance. Fuzzification and defuzzification comprise mapping the essential fuzzy variable to crisp number employed by the control system. Fuzzifications convert a numeric value for the error (*e*) or change of error (*e*) into a linguistic value such as positive big (PB), positive small (PS), zero (ZE), negative big (NB), and negative small (NS) with a membership level. In contrary, defuzzification takes the fuzzy output of the rules and creates a crisp numeric value used as the control input to the plant. The FLC membership functions are defining over the range of input and output variable values and represent the variable's universe of discourse linguistically. Fig. 4 shows the membership function of the controller. The outline of the input rules was shown in Table 2. Fig. 5 shows the surface generated due to the rules. In the current research, some limits, as given in Table 3, were allocated for all the states, seat travel distance, seat travel velocity, and actuator forces.

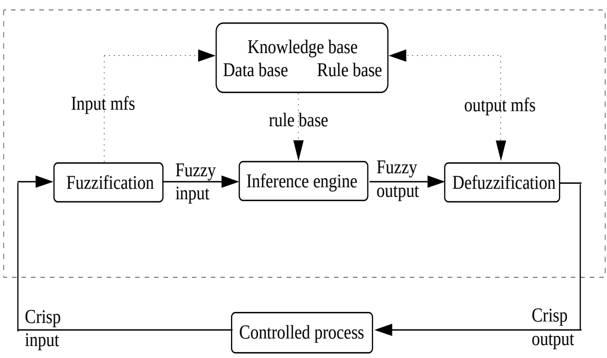

Fig. 3: Block diagram representation of FLC

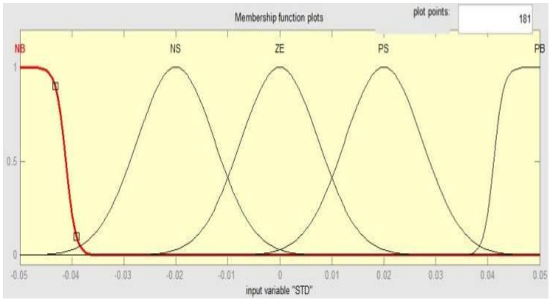

Fig. 4(a): Membership functions of error

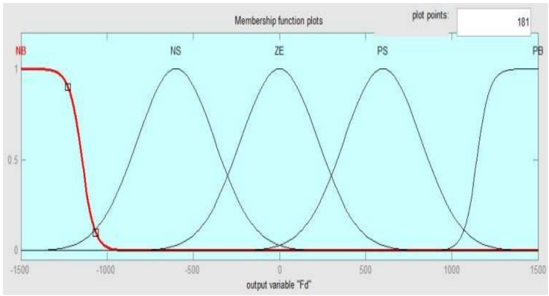

Fig. 4(b): Change of error

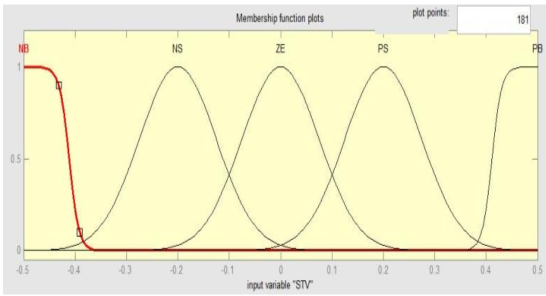

Fig. 4(c): Control output

Table 2: FLC rules

Fa		Change of error of suspension working space						
		NB	NM	NS	ZE	PS	PM	PB
Error of suspension working space	NB	NB	NB	NB	NB	NM	NS	ZE
	NM	NB	NB	NB	NM	NS	ZE	PS
	NS	NB	NB	NM	NS	ZE	PS	PM
	ZE	NB	NM	NS	ZE	PS	PM	PB
	PS	NM	NS	ZE	PS	PM	PB	PB
	PM	NS	ZE	PS	PM	PB	PB	PB
	PB	ZE	PS	PM	PB	PB	PB	PB

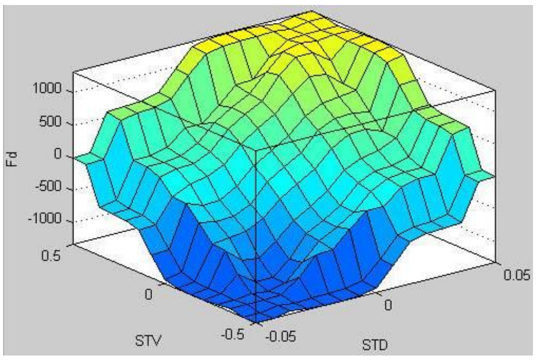

Fig. 5: Surface generated due to the rules

Table 3: Variable limits assigned for the controller design

Variable	Limits	Variable	Limits
x_{p1}, x_{p2}	[-0.05, 0.05]	F_{a1}	[-1500, 1500]
$\dot{x}_{p1}$, $\dot{x}_{p2}$	[-0.5, 0.5]	F_{a2}	[-1500, 1500]

5. Results and discussions

The results that have been obtained for a passive and active suspension with the use of FLC of half vehicle model with random road profile as input using Matlab/Simulink. Figs. 6 and 7 show the time response plots of car body displacement and car body acceleration, of both passive and active suspension system in that order. It is observed that there is more significant enhancement with FLC than the passive system when the vertical displacements and accelerations of the vehicle are considered. Figs. 8 and 9 present the uncontrolled and controlled suspension time response of a passenger seat displacement and acceleration. There is a significant attainment in vibration amplitudes that are decreased.

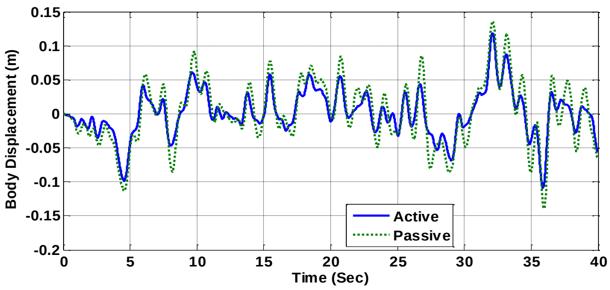

Fig. 6: Car body disp. of passive & active suspension systems

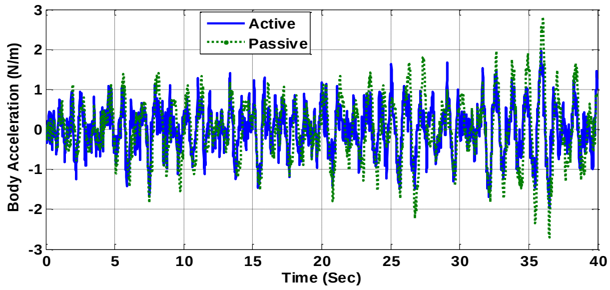

Fig. 7: Car body acceleration of passive & active susp. systems

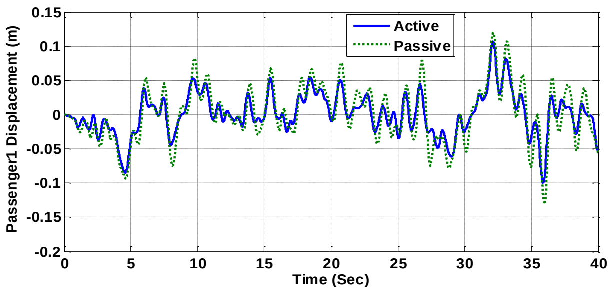

Fig. 8: Driver disp. of passive & active suspension systems

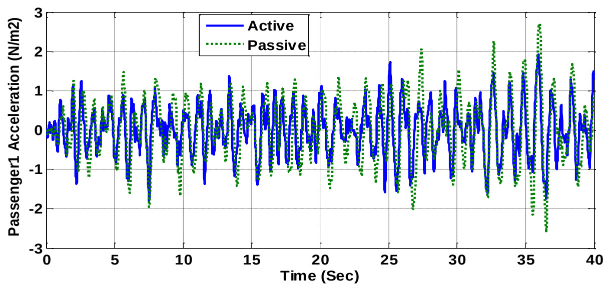

Fig. 9: Driver acceleration of passive & active suspension systems

Figs. 10 and 11 explain the uncontrolled and controlled systems of the front tire displacement and pitch motion. The outcomes disclose that there is a significant attainment in vibration amplitudes that are decreased. Figs. 12 and 13 display the passenger displacement, and acceleration, which can be noted that there is an observed enhancement in both displacement and acceleration due to the control. Figs. 14 and 15 show the rear tire displacement, and the generated forces of front and rear actuators.

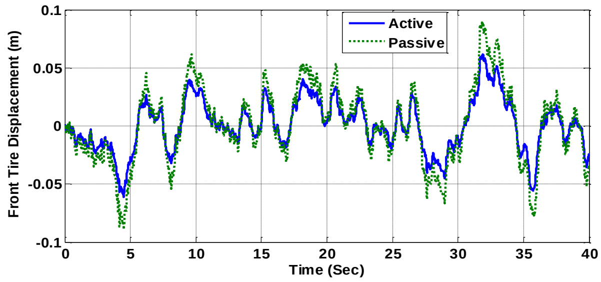

Fig. 10: Front tire disp. of passive & active suspension systems

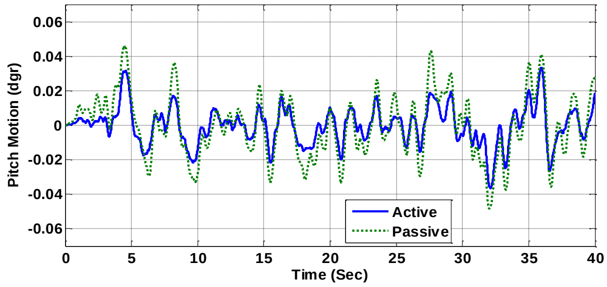

Fig. 11: Pitch motion of passive & active suspension systems

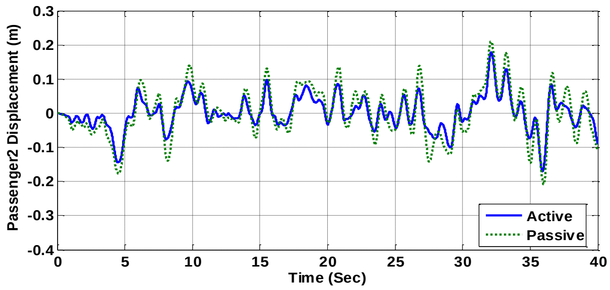

Fig. 12: Passenger disp. of passive & active suspension systems

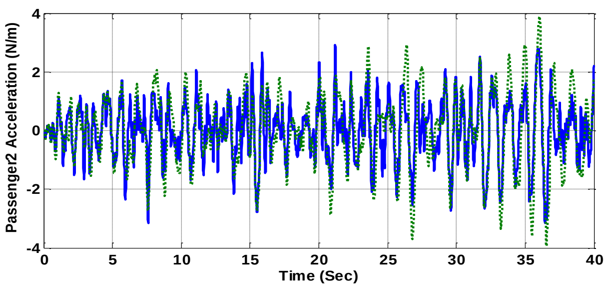

Fig. 13: Passenger acceleration of passive & active susp. systems

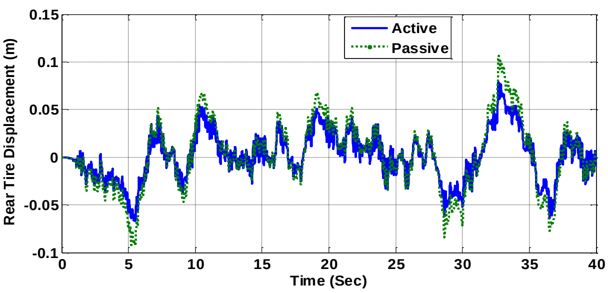

Fig. 14: Rear tire displ. of passive & active suspension systems

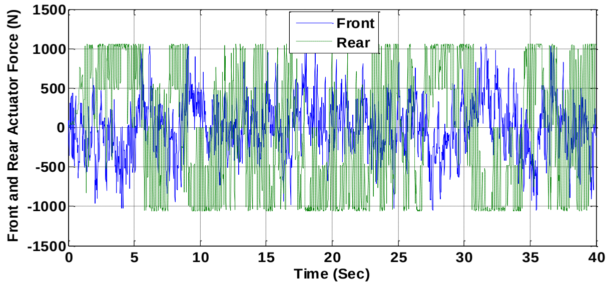

Fig. 15: Front and rear actuator forces of active suspension system

6. Conclusions

This paper has applied the FLC in an active automotive suspension system. A mathematical model of half vehicle active suspension having six degrees of freedom and two input forces generated by two separate actuators was simulated using Matlab/Simulink. The controller was designed using driver travel displacement and velocity feedback for the suspension system to decrease the vibrations amplitude of the driver and passenger seats. The car body displacement, body acceleration and tire deflection were evaluated in time domain to quantify the efficiency of the suspension under random road disturbance. The active suspension system based on the fuzzy logic has evidently provided an enhancement of suspension performance related to ride comfort and vehicle stability compared with passive system.

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