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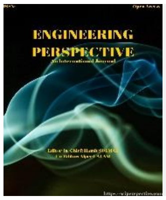

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Research Paper

Quarter Car Active Suspension System Control Using Fuzzy Controller

Turan Alp Arslan[1], Faruk Emre Aysal[2*], İbrahim Çelik[2], Hüseyin Bayrakçeken[1], Tuğçe Nur Öztürk[2]

[1] *Automotive Engineering Department, Faculty of Technology, Afyon Kocatepe University, Afyonkarahisar, 03200, Türkiye*
[2]*Mechatronics Engineering Engineering, Faculty of Technology, Afyon Kocatepe University, Afyonkarahisar, 03200,*

ABSTRACT

The performance of active suspension systems is directly related to the mechanical design and control of the system. The stable operation of the controller improves driving comfort and handling. The quarter car model is frequently used in the analysis of suspension systems due to its simple structure. In this study, Matlab Simulink software was used in the modeling, control and simulation of the quarter car active suspension model. System performance was investigated for four different road profiles with PID and fuzzy logic control methods. Two of the road profiles used are in the form of impact signals consisting of pits and bumps. The other two road profiles are random road disturbances with high frequency. The effects of active and passive suspension systems on driving comfort are compared by taking into account the control methods used. As a result of the study, it has been determined that the fuzzy logic controller gives better results in pulse signals consisting of bumps and pits, and the PID controller gives better results in high-frequency random road disturbances. In addition, with the use of fuzzy logic control method in the active suspension system, a significant decrease in the actuator force has occurred. This result is very interesting in terms of minimizing energy, reducing actuator sizes and reducing costs.

Keywords: Active suspension, Fuzzy logic, Quarter car model, Vehicle dynamics.

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Author Contacts
**Corresponding Author*
e-mail addresses : talparslan@aku.edu.tr, faysal@aku.edu.tr*, icelik@aku.edu.tr, bceken@aku.edu.tr, tugcenurozturk06@gmail.com.
Orcid numbers : 0000-0003-3259-4854, 0000-0002-9514-1425, 0000-0002-8857-1910, 0000-0002-1572-4859, 0000-0003-0354-8058

1. Introduction

Irregularities on the roads adversely affect the comfort and safety of vehicles. For this reason, suspension systems in various designs have been used in vehicles since the end of the 19th century. Vehicle suspension systems play an important role in reducing the vertical acceleration of the chassis and providing comfortable and safe driving. Today, classical suspension systems consisting of coil springs and damping elements on each wheel are used as standard in passenger vehicles [1,2].

The traditional suspension system used in passenger vehicles consists of three basic components: shock absorber, coil spring and connecting elements. Here, the shock absorber performs the duty of absorbing the shocks originating from the road, and the coil spring performs the task of storing the energy coming to the chassis. The connecting elements provide the connection between the wheel hub and the suspension elements and the connection between the chassis and the suspension. Traditionally, systems with constant damping and spring coefficient, known as passive suspension systems, are used in vehicles. Suspension systems whose damping properties or vertical acceleration ability can be adjusted by a control element are known as active suspension systems. In order to improve driving comfort and safety, researchers carry out many studies on systems known as active suspension systems [3-9].

Various approaches are discussed as a control element in active suspension systems. It is a common approach to use Magneto-Rheological (MR) fluid instead of the hydraulic fluid used in the shock absorber system. By using MR fluid, hydraulic fluid viscosity can be changed by a control current. Thus, the damping rate of the shock absorber can be actively controlled. This approach is accepted as a semi-active suspension system in the literature [10-13]. Another widely considered approach is to add a linear actuator to the conventional suspension system. Thanks to the additional force provided by this actuator, the vertical acceleration in the suspension system becomes controllable. This form of suspension system is known as active suspension [14-19].

Stable control of active and semi-active suspension systems is an important problem for the widespread use of these systems. For this reason, many different control approaches are considered by researchers. Various methods such as optimal control theory, feedback control system, robust, LQR, PID, fuzzy logic are used for the control of the active suspension system [20-27].

Fuzzy logic is accepted as an important solution method for dynamic systems that want to be controlled adaptively. Therefore, there are many studies on the development of control algorithms using fuzzy logic in active suspension systems. Studies show that fuzzy logic controllers provide successful results for active suspension systems. However, it is seen that the majority of the studies carried out are on simulation and mathematical modeling [28-37]. Therefore, the improvement of the control approaches by comparing them with different methods and making real applications in the following stages is still a topic of current study.

In this study, active suspension system control was realized by using PID and fuzzy logic control methods. MATLAB Simulink software was used for modelling, control and simulation studies of the quarter car active suspension system. Passive and active suspension system results were obtained for four different road profiles. The displacement, velocity, acceleration and actuator controls of the vehicle body were examined and the superiority of PID and fuzzy logic control methods over each other was investigated. The effects of the control structures created in the simulation results on the driving comfort and control force are discussed.

2. Quarter Car Active Suspension Model

The quarter car model has a simple and easy-to-understand structure. It is frequently used in suspension system design and simulation because it reflects the important features of the full car. The passive quarter car model has two main masses, spring and unsprung, two springs and a damper. This system is activated with the actuator added between the body and the axle. Actuators, which generally consist of electro-hydraulic elements, provide the control of the system by generating forces in both directions. With the system control, the effects of vibrations caused by road disturbances on the vehicle body and passengers are reduced [38, 39]. The quarter car active suspension model with 2 degrees of freedom is shown in Figure 1.

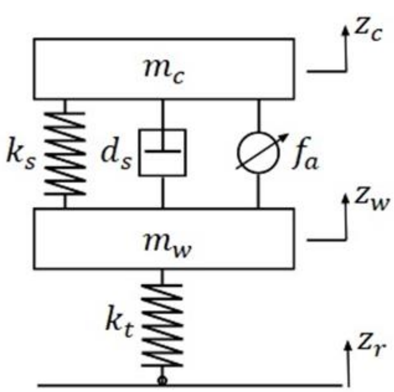

Figure 1. Quarter car active suspension model

In this model, the spring mass m_c, which corresponds to one fourth of the vehicle body mass, is represented by the unsprung mass of the axle and wheel components m_w, the passive components of the spring and damper coefficients k_s and d_s, respectively, the tire stiffness k_t and the control force produced by the actuator f_a. In addition, the displacement of the spring and unsprung masses are indicated by z_c and z_w, respectively, and the road profile affecting the unsprung mass is indicated by z_r. The constant parameters of the quarter car active suspension system are shown in Table 1.

Table 1. Parameters of active suspension system

Parameters	Values
m_c (kg)	300
m_w (kg)	50
k_s (N/m)	18000
k_t (N/m)	190000
d_s (N-s/m)	2000

The linear equations of motion for the spring and unsprung masses of the system are defined using Newton's second law as follows:

$$m_w \ddot{z}_w = k_t(z_r - z_w) - k_s(z_w - z_c) - d_s(\dot{z}_w - \dot{z}_c) - f_a \quad (1)$$

$$m_c \ddot{z}_c = k_s(z_w - z_c) + d_s(\dot{z}_w - \dot{z}_c) + f_a \quad (2)$$

In order to develop the state space model of the system x_1, x_2, x_3 and x_4 parameters are accepted as state variables. Here x_1 represents the displacement of the unsprung mass, x_2 the velocity of the unsprung mass, x_3 the displacement of the spring mass and x_4 the velocity of the spring mass. Quarter car active suspension model equations of motion are converted into state space model with the help of the following expressions:

$$x_1 = z_w \quad (3)$$

$$x_2 = \dot{z}_w \quad (4)$$

$$x_3 = z_c \quad (5)$$

$$x_4 = \dot{z}_c \quad (6)$$

$$\dot{x}_1 = x_2 \quad (7)$$

$$\dot{x}_2 = \frac{1}{m_w}[k_t z_r - (k_t + k_s)x_1 - d_s x_2 + k_s x_3 + d_s x_4 - f_a] \quad (8)$$

$$\dot{x}_3 = x_4 \quad (9)$$

$$\dot{x}_4 = \frac{1}{m_c}[k_s x_1 + d_s x_2 - k_s x_3 - d_s x_4 + f_a] \quad (10)$$

The state space model used to explain the system dynamics is obtained as follows:

$$\dot{x} = Ax + Bu \quad (11)$$

$$y = Cx \quad (12)$$

$$x = [x_1, x_2, x_3, x_4]^T \quad (13)$$

$$u = [f_a, z_r]^T \quad (14)$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{k_t + k_s}{m_w} & -\frac{d_s}{m_w} & \frac{k_s}{m_w} & \frac{d_s}{m_w} \\ 0 & 0 & 0 & 1 \\ \frac{k_s}{m_c} & \frac{d_s}{m_c} & -\frac{k_s}{m_c} & -\frac{d_s}{m_c} \end{bmatrix} \quad (15)$$

$$B = \begin{bmatrix} 0 & 0 \\ -\frac{1}{m_w} & \frac{k_t}{m_w} \\ 0 & 0 \\ \frac{1}{m_c} & 0 \end{bmatrix} \quad (16)$$

$$C = [0 \quad 0 \quad 1 \quad 0] \quad (17)$$

3. Controller Design

In the study, two types of controllers were used to control the quarter car active suspension. These are proportional-integral-derivative (PID) controller and fuzzy logic (FLC) controller.

PID controllers are a very common form of control in control systems due to their simple structure, low number of variables to be adjusted and ease of physical implementation. This controller, which has three parameters as proportional (P), integral (I) and derivative (D), determines the amount of error by comparing the signal coming from the system output with the reference signal. Depending on the set variables, the controller effect is sent to the output, thus minimizing the error. The mathematical formula of the PID controller working with continuous feedback is as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{d}{dt} e(t) \quad (18)$$

Here K_p is the proportional gain, K_i integral gain, K_d derivative gain, e(t) is the difference between the set point and the measured process variable at the relevant time, and u(t) is the controller effect on the process at the relevant time. PID controller performance is directly based on accurate determination of controller gains [40].

The MATLAB Simulink model of quarter car active suspension system controlled by a PID controller is shown in Figure 2. In this study, the displacement of the spring mass z_c, which corresponds to one fourth of the vehicle body mass, is fed back to the system. The road profile z_r acting on the unsprung mass is accepted as the reference signal. The PID controller output, on the other hand, affects the system again as the activation force f_a.

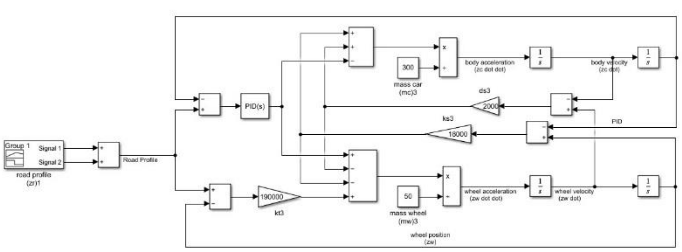

Figure 2. Simulink model of active suspension system using PID controller

Fuzzy logic basically tries to imitate the decision-making style that takes place in the human brain. In this method, where it is accepted that the decisions are not final, quantitative and binary, the answers may be in shades of gray, not black and white [41]. The fuzzy logic controller consists of three parts: the fuzzifier, the inference unit and the defuzzifier. The fuzzifier is responsible for converting the input values to fuzzy values, the inference unit is responsible for processing the data and calculating the controller outputs, and the defuzzifier is responsible for converting the outputs to real numbers [42]. In fuzzy logic applications, it is of great importance that the input-output parameters, membership functions and control rules are set correctly by the expert.

The vertical displacement and velocity of the system are fuzzy logic inputs in this study. These input parameters can also be defined as error and change of error. The output parameter of the controller is the control force desired to be effected on the system with the help of the actuator. The fuzzy logic input parameters are expressed as follows:

$$fuzzy_{input1} = z_c - z_r \quad (15)$$

$$fuzzy_{input2} = \dot{z}_c - \dot{z}_r \quad (16)$$

In Figures 3 and 4, membership functions of fuzzy logic input parameters are seen, and in Figure 5, membership functions of the output parameter are seen. Inputs and output have five trapezoidal membership functions. In these figures, NB, NS, Z, PS, and PB denote negative big, negative small, zero, positive small, and positive big, respectively.

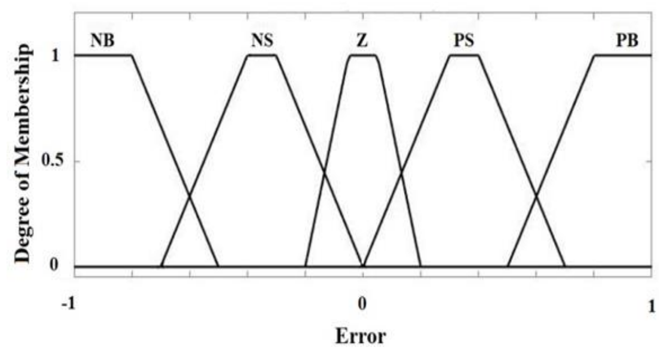

Figure 3. Membership functions for error

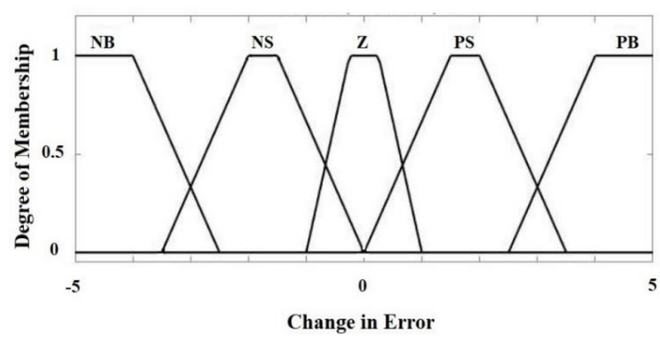

Figure 4. Membership functions for change in error

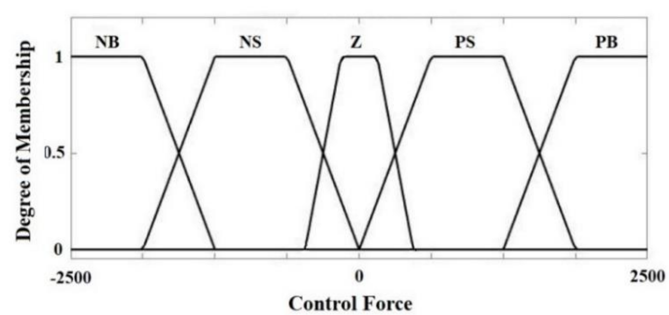

Figure 5. Membership functions for control force

The rule base created for the quarter car active suspension system is created based on the expert's knowledge and experience, as in other applications. The fuzzy logic rule matrix of the study, in which the classical "Mamdani" approach was used for the rule base, is shown in Table 2. There are 25 control rules in total in the created rule base.

Table 2. Fuzzy logic rule matrix

e/Ce	NB	NS	Z	PS	PB
NB	NB	NB	NS	NS	Z
NS	NB	NS	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PS	PB
PB	Z	PS	PS	PB	PB

NB: Negative Big; NS: Negative Small; Z: Zero; PS: Positive Small; PB: Positive Big; e: Error; Ce: Change in Error

Figure 6 shows the fuzzy logic surface plot for the input and output parameters, and the MATLAB Simulink model of the quarter car actie suspension controlled by a fuzzy logic controller is shown in Figure 7.

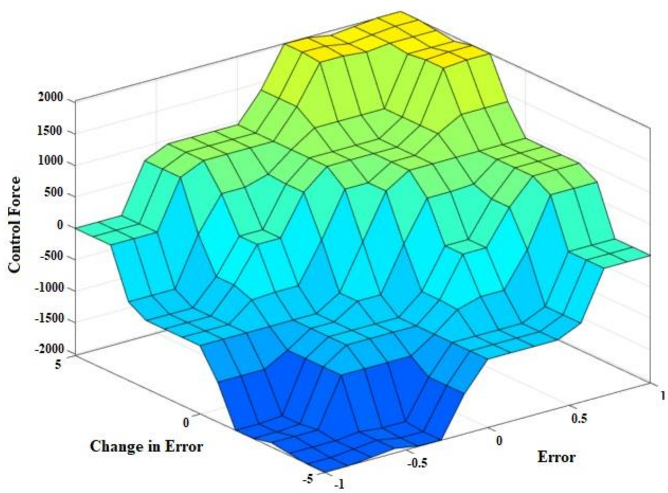

Figure 6. Fuzzy logic surface plot

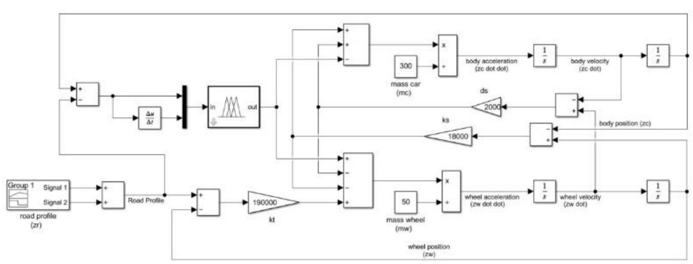

Figure 7. Simulink model of active suspension system using fuzzy logic controller

4. Simulation Results

In this study, active suspension quarter car suspension system control was carried out with two different controllers, PID and FLC. MATLAB Simulink software was used in the modeling, control and simulation of the system. The effects of the control structures created in the simulation results on the driving comfort and control force were investigated. The performance of the simulation models was investigated for four different road profiles. In order to best observe the active suspension characteristics and controller effects, two of the road profiles were created from potholes and bumps, while the other two were created from high frequency random road disturbances. Interesting results emerged when the displacement amount of the spring mass z_c, which represents the vehicle body for all road profiles, was analysed. The variation of the spring mass displacement z_c with time for the first road profile simulating a bump and then a pit is shown in Figure 8.

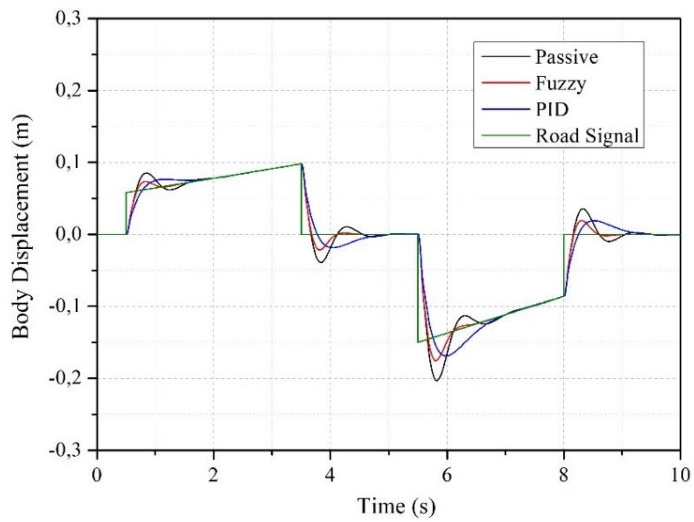

Figure 8. Body displacement for first road profile

When the figure is examined, it is clearly seen that the control application with PID and fuzzy logic controller in the active suspension system provides an improvement in driving comfort. For the first road profile, it can be said that fuzzy logic control gives better results than PID controller with fast rise time and fast settling time. In the PID controller, the amount of overshoot is close to that of fuzzy logic, but the system becomes stable in a longer time. When the passive suspension performance is examined, it is seen that the settling time and the overshoot amount of the system are quite high. Both control structures have reduced the amount of body displacement, amplitude and frequency compared to the passive suspension.

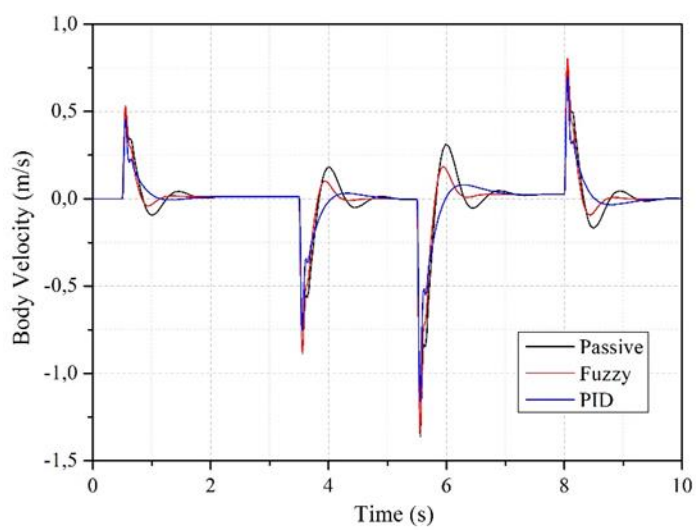

Figure 9. Body velocity for first road profile

It is clearly seen that the fuzzy logic and PID control signal amplitude is less than half of the passive suspension signal. The variation of spring mass velocity $\dot{z}_c$ and spring mass acceleration $\ddot{z}_c$ for the first road profile with time is shown in Figure 9 and Figure 10, respectively.

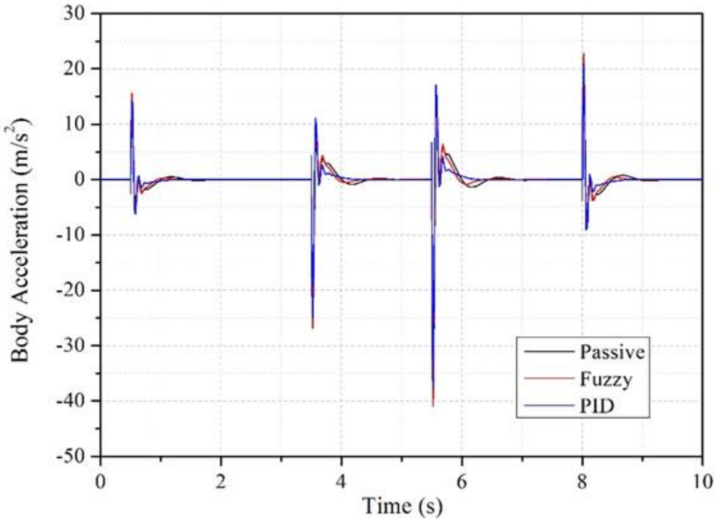

Figure 10. Body acceleration for first road profile

When the body velocity and acceleration results are examined, it is seen that the maximum values for all models are close to each other. However, as in the amount of body displacement, the active suspension system controlled by fuzzy logic has become stable in a shorter time. This indicates an improvement in driving comfort. The time-dependent variation of the control force f_a obtained as a result of the simulation carried out for the first road profile is shown in Figure 11.

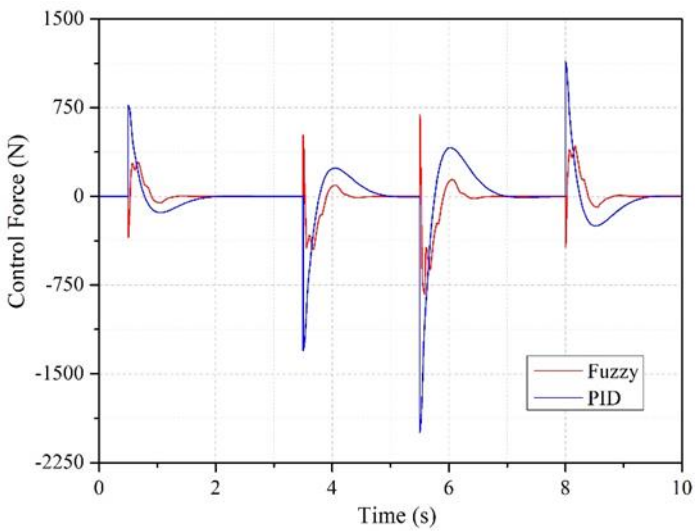

Figure 11. Control force for first road profile

With the use of fuzzy logic controller, decreases were observed in the active suspension control force compared to the PID controller. This will enable the use of smaller and lower cost actuators with fuzzy logic control. Minimizing the amount of energy used, reducing the size of the actuator element to be used on a moving vehicle and reducing costs are as important as improving driving comfort. While the system controlled by PID controller needs an actuator force of 1850 N, this force has decreased to 760 N with fuzzy logic control. The variations of the vehicle body displacement z_c for other simulated road conditions with time are shown in Figures 12, 13 and 14.

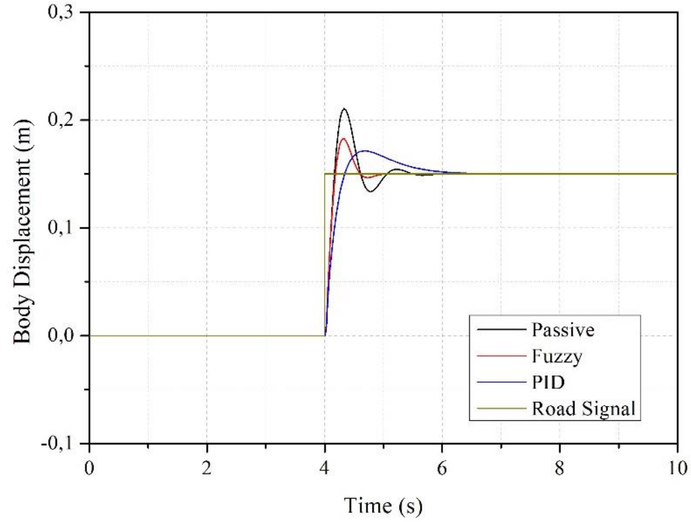

Figure 12. Body displacement for second road profile

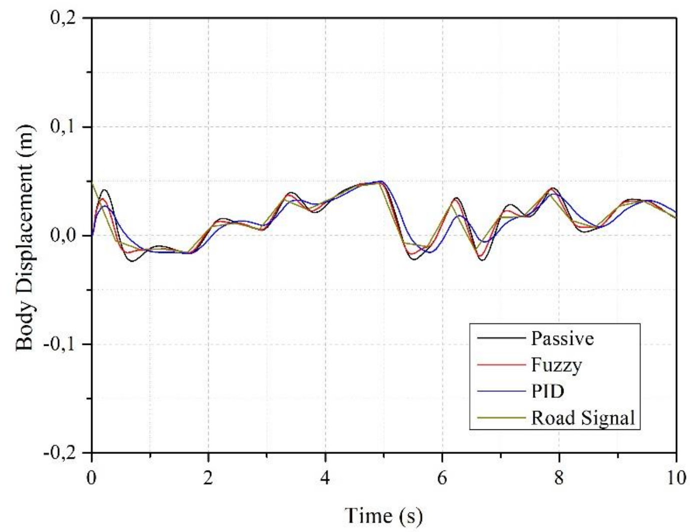

Figure 13. Body displacement for third road profile

In the second road profile with a bump signal, it is seen that the displacement amount for the fuzzy logic-controlled system is slightly higher than the PID controlled system. However, as in the first road profile, a more stable body movement occurred with rapid rise and settling times. Although the displacement is low in the PID controlled system, it is not acceptable for the signal setting time to take about 1 second. In addition, both PID and fuzzy logic results will provide better driving comfort compared to the passive suspension system. High amplitude and oscillation in the passive suspension system signal will adversely affect driving comfort. When the results for the third and fourth road profiles where random disturbances are defined are examined, it is seen that the active suspension system using PID controller provides better results with low body displacement. While the fuzzy logic controller stands out in bumps and potholes that can be described as pulse signals, the PID controller has an advantage in continuous road disturbances with high frequency.

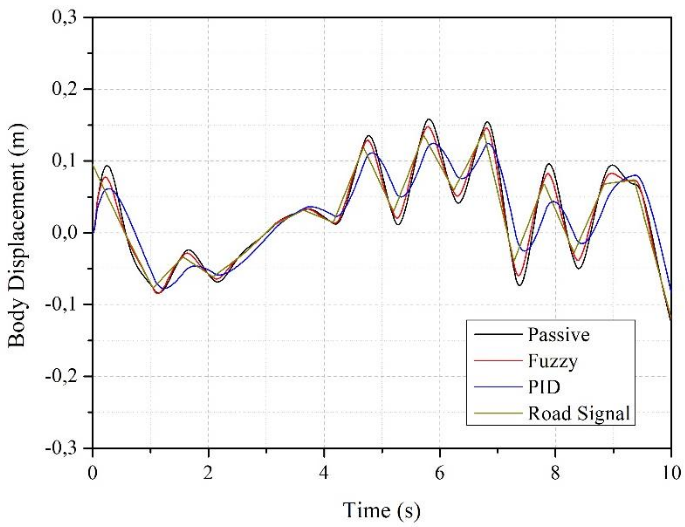

Figure 14. Body displacement for fourth road profile

5. Conclusion

In this study, PID and fuzzy logic control methods are used for active suspension control. MATLAB Simulink software was used in the modeling, control and simulation of the quarter car active suspension system. The simulation results for four different road profiles were compared with each other and with the passive suspension system. Compared to the passive suspension system, it has been found that both methods effectively stabilize the suspension system and provide significant improvements in driving comfort. As a result of the study, it has been confirmed that both PID and fuzzy logic control give successful results in active suspension system control. The fuzzy logic controller has come to the forefront with its low oscillation, short rise and settling time in road disturbances that can be defined as an impact signal consisting of pits and bumps. In high frequency random path disturbances, the system with PID controller has an advantage with its low displacement amount. With the use of fuzzy logic control, a 59% decrease in actuator control force has occurred. This value is very interesting in terms of reducing the actuator dimensions, reducing the costs and minimizing the energy used. It is thought that testing different control methods and different disturbance inputs on half or full vehicle models will be beneficial for the development of active suspension systems.

Nomenclature

Ce	change in error
e	error
d_s	suspension damping coefficient (N-s/m)
f_a	actuation force (N)
FLC	Fuzzy Logic Controller
k_s	suspension stiffness (N/m)
k_t	tyre stiffness (N/m)
K_d	derivative gain
K_i	integral gain
K_p	proportional gain
LQR	Linear Quadratic Regulator
m_c	sprung mass (kg)
m_w	unsprung mass (kg)
MR	Magneto-Rheological
PID	Proportional Integral Derivative
u	controller effect
z_c	displacement of sprung mass(m)
z_r	road profile (m)
z_w	displacement of unsprung mass (m)

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Turan Alp Arslan: Conceptualization, Writing-original draft, Validation, **Faruk Emre Aysal:** Conceptualization, Writing-original draft, Supervision, **İbrahim Çelik:** Conceptualization, Formal analysis, **Hüseyin Bayrakçeken:** Conceptualization, Supervision, **Tuğçe Nur Öztürk:** Formal analysis

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