ACTIVE SUSPENSION OF CARS USING FUZZY LOGIC CONTROLLER OPTIMIZED BY GENETIC ALGORITHM

R. K. Pekgökgöz, M. A. Gürel, M. Bilgehan, M. Kısa*
Harran University, Civil Engineering Department, Şanlıurfa-TURKEY
[*]Harran University, Mechanical Engineering Department, Şanlıurfa-TURKEY

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Abstract

In the literature, there are many studies based on adaptive control methods to improve the properties of the vehicle suspension systems. In this work, fuzzy logic is used to control the active suspension and the membership functions are optimized by using genetic algorithm operations. By using the fuzzy logic and proportional, integral, derivative (PID) controller methods, the vehicle body deflections and the control force have been obtained and compared with each others. These comparisons displayed the efficiency and convenience of the offered fuzzy logic controller (FLC) method. The study shown that the proposed method can be used for the active control of car suspension systems.

Key words: Active suspension systems, fuzzy logic control, genetic algorithm, PID control, quarter-car reference model

1. Introduction

Suspension systems are the most important part of the vehicle affecting the ride comfort of passengers and road holding capacity of the vehicle, which is crucial for the safety of the ride [1]. Designing a good suspension system with optimum vibration performance under different road conditions is an important task. Over the years, both passive and active suspension systems have been proposed to optimize the vehicle quality [2,3]. Passive suspension systems use conventional dampers to absorb vibration energy and do not require extra power. Whereas, active suspension systems capable of producing an improved ride quality use additional power to provide a response-dependent damper [4,5]. In active suspension systems, an actuator (linear motor, hydraulic cylinder, etc.) parallel to the suspension systems is placed between the wheel and the vehicle body. The actuator uses the suspension space while pulling down or pushing up the vehicle body in order to suppress its vibrations due to the road irregularities.

The primary performance of a suspension system is traditionally evaluated in terms of ride quality [6] The two principal variables for the design and evaluation of the suspension systems are vehicle body acceleration, which determines ride comfort, and suspension deflection, which indicates the limit of the vehicle body motion [7]. In the literature, the root mean square of vertical accelerations of the vehicle body is often taken as the performance criterion (objective function) to be optimized [8].

The control of active suspension systems has been developed using optimal control theory [9], in which the problem of constructing an active suspension system is equivalent to the problem of determining the optimal control to minimize a performance index. It is a well-known fact that the derivation of the control needs the vehicle dynamics to be accurately expressed as a linear model, whereas the vehicle dynamics generally includes nonlinearities and uncertainties [10].

For the design of active suspension systems for quarter car models, the use of FLC method has been proposed, with a satisfactory performance [11,12,13,14] Applied genetic algorithm to vehicle suspension design, in which the road surface is assumed to be a deterministic sinusoidal function[8]. Using minimum pavement load as the main criterion, designed a genetic algoritm-based optimum suspension for vehicles [5].

The main objective of this paper is to propose a new active suspension system for passenger cars, using suspension deflection of the vehicle body as the principal criterion of control, and fuzzy-logic control as the complementary control. The membership function values of considered fuzzy model are optimized by genetic algoritm method for the minimizing the maximum of relative deflection between the vehicle body and the suspension parts, and taking into account the physical restrictions of the system. It must be noted that, since the determination of the wheel deflection is difficult, it is neglected in the presented analysis. As it will be seen, the proposed active suspension system particularly has an advantage with respect to the reduction of maximum vehicle body deflections.

2. Calculation model and design requirements

Calculation model and the parameters used in the present study have been taken from study of [15]. The model and parameters are shown in Figure 1. As can be seen from the figure, a quarter car model is considered. In the figure, m_b is the mass of the one quarter of the total car, m_w is the wheel mass, k_1 is the spring constant (stiffness) of the suspension spring, k_2 is the spring constant (stiffness) of the tire, c_1 is the damping coefficient of the suspension systems damper, c_2 is the damping coefficient of the tire, u is the desired force by the cylinder, x_1 is the body displacement, x_2 is the whell displacement and w is the road input.

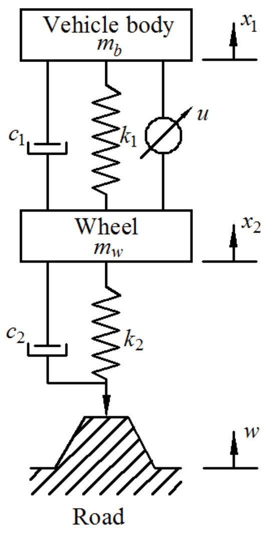

Fig.1. One quarter car model

When a car meets to any obstacle or dent during riding, resulting vibrations must be certainly dissipated in a short period of time. As the system output, the suspension deflections, x_1-x_2, is chosen instead of the whole system deflection, x_1-w, because of the difficulties in determining of the wheel deflections, as mentioned above. Road surface input, w, Figure 1 can be accepted as a unit step input. The output, x_1-x_2, of the planned feed-back control system, is not permitted to exceed the 5% of the unit step input, w, and the dissipation of the vibrations is required to occur in a time shorter than 5 seconds. For example, if the car body runs into a road surface roughness of 10 cm hight, the output must be smaller than ± 5 mm, and the vibrations must vanish in 5 seconds.

As it can be seen from the Figure 1 the model has two degrees of freedom. This model uses an actuator to produce the control force between the vehicle body mass and the wheel mass. The equations of motion of the car body and wheel are as follows:

$$m_b\ddot{x}_1 = -c_1(\dot{x}_1 - \dot{x}_2) - k_1(x_1 - x_2) + u \tag{1}$$

$$m_w\ddot{x}_2 = c_1(\dot{x}_1 - \dot{x}_2) + k_1(x_1 - x_2) + c_2(\dot{w} - \dot{x}_2) + k_2(w - x_2) - u \tag{2}$$

In the calculations the parameters m_b, m_w, k_1, k_2, c_1 and c_2; 2500 kg, 320 kg, 80000 N/m, 500000 N/m, 350 Ns/m and 15020 Ns/m, respectively.

3. Car suspension systems designed with PID controller

The PID controllers (in which P, I and D stand for proportional, integral and derivative, respectively) have been used to control various engineering systems such as suspensions, and DC motors. In this study, the results of the FLC are going to be compared with those of PID controller. Consequently, firstly, the PID controller is introduced. In this control method, with the aid of the Laplace transform, two transfer functions are derived. As known, the Laplace transform is one of the mathematical tools used for the solution of linear ordinary differential equations. In comparison with classical linear differential equation solving techniques, the Laplace transform has a simple construction. Utilizing the Laplace transform, the transfer functions $G_1(s)$ and $G_2(s)$ are derived from the equations of motions (Eq. (1) and Eq. (2)) as follows.

$$G_1(s) = \frac{x_1(s) - x_2(s)}{u(s)} = \frac{(m_b + m_w)s^2 + c_2 s + k_2}{\Delta} \tag{3}$$

$$G_2(s) = \frac{x_1(s) - x_2(s)}{w(s)} = \frac{-m_b c_2 s^3 - m_b k_2 s^2}{\Delta} \tag{4}$$

where,

$$\Delta = \det\begin{bmatrix} (m_b s^2 + c_1 s + k_1) & -(c_1 s + k_1) \\ -(c_1 s + k_1) & (m_w s^2 + (c_1 + c_2)s + (k_1 + k_2)) \end{bmatrix} \tag{5}$$

and s is the variable known as Laplace operator which is a complex variable in the form of $s = \alpha + i\,\beta$. As it can be understood from the Eq. (3) and (4) each of the transfer functions is obtained as the ratio of system output to the respective system input.

For the car suspension model given in Figure 1., the PID controller block diagram is shown in Figure 2., in which u and w are system inputs and x_1-x_2 is the system output, as expressed previously. This block diagram has a closed loop structure. The loop begins the control, with zero initial value of $r = 0$ and an assigned value of w. Then, it takes the difference of the obtained system input value and the first initial value as new initial condition. The other calculations are performed by the procedure given before. When the design requirements are satisfied, it stops the calculation.

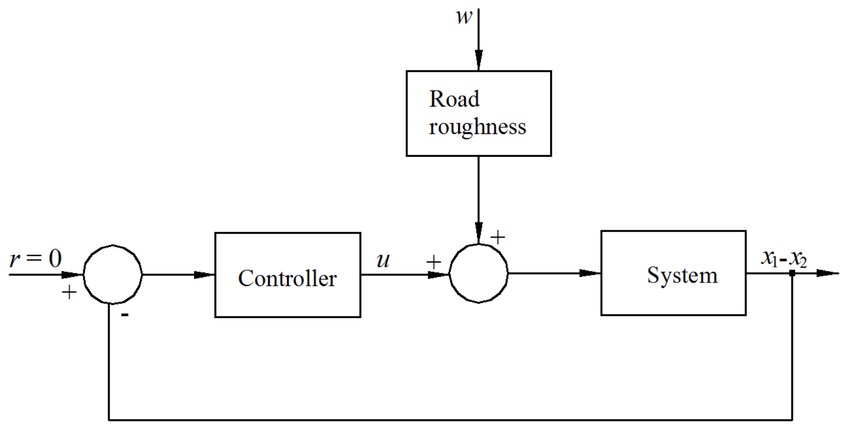

Fig. 2. Car suspension systems belonging to block diagram

Taking into account the proportional gain K_p, integral gain K_I, and derivative gain K_D in the transfer function expressions of Eq. (3) and (4), the general equation of PID control is obtained as follows:

$$K_p + \frac{K_I}{s} + K_D s = \frac{K_D s^2 + K_p s + K_I}{s} \quad (6)$$

The values of gains determined by the "root curve seat method" are explained in reference (Bingöl, 2005). Taking the values for m_b, m_w, k_1, k_2, c_1 and c_2 as stated in section 2, the root curve seat method gives, for a good controller, 1664200, 1248150 and 416050 values for K_p, K_I and K_D gains, respectively. Figure 3 shows the PID controller Simulink model of the considered car suspension system. In this model, the controller block uses the K_p, K_I and K_D gains, and the suspension system model block contains the general Simulink model of the car suspension system given in Figure. 4.

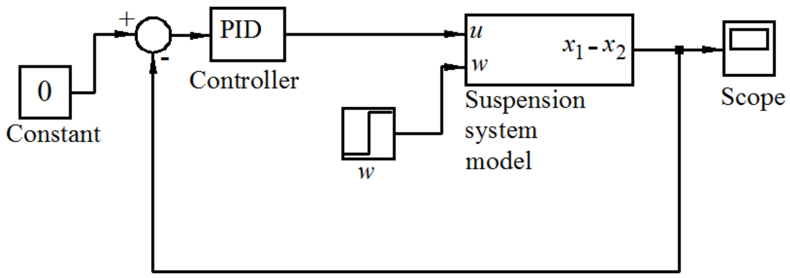

Fig. 3. PID controller Simulink model for suspension system

4. Design of fuzzy logic controller (FLC) suspension system

The FLC used in the active suspension has three inputs that are body acceleration $\ddot{x}_1$, body velocity $\dot{x}_1$, body deflection velocity $\dot{x}_1 - \dot{x}_2$, and one output which is desired actuator force u. The control system itself consists of three stages: fuzzification, fuzzy inference machine and defuzzification.

The fuzzification stage converts real-number (crisp) input values into fuzzy values, while the fuzzy inference machine processes the input data and computes the controller outputs in cope with the rule base and data base. These outputs, which are fuzzy values, are converted into real-numbers by the defuzzification stage.

Table 1. Rule base of the FLC model

$\dot{x}_1 - \dot{x}_2$	$\dot{x}_1$	$\ddot{x}_1$	u	$\dot{x}_1 - \dot{x}_2$	$\dot{x}_1$	$\ddot{x}_1$	u
PM	PM	ZE	ZE	PM	PM	P or N	NS
PS	PM	ZE	NS	PS	PM	P or N	NM
ZE	PM	ZE	NM	ZE	PM	P or N	NB
NS	PM	ZE	NM	NS	PM	P or N	NB
NM	PM	ZE	NB	NM	PM	P or N	NV
PM	PS	ZE	ZE	PM	PS	P or N	NS
PS	PS	ZE	NS	PS	PS	P or N	NM
ZE	PS	ZE	NS	ZE	PS	P or N	NM
NS	PS	ZE	NM	NS	PS	P or N	NB
NM	PS	ZE	NM	NM	PS	P or N	NB
PM	ZE	ZE	PS	PM	ZE	P or N	PM
PS	ZE	ZE	ZE	PS	ZE	P or N	PS
ZE	ZE	ZE	ZE	ZE	ZE	P or N	ZE
NS	ZE	ZE	ZE	NS	ZE	P or N	NS
NM	ZE	ZE	NS	NM	ZE	P or N	NM
PM	NS	ZE	PM	PM	NS	P or N	PB
PS	NS	ZE	PM	PS	NS	P or N	PB
ZE	NS	ZE	PS	ZE	NS	P or N	PM
NS	NS	ZE	PS	NS	NS	P or N	PM
NM	NS	ZE	ZE	NM	NS	P or N	PS
PM	NM	ZE	PB	PM	NM	P or N	PV
PS	NM	ZE	PM	PS	NM	P or N	PB
ZE	NM	ZE	PM	ZE	NM	P or N	PB
NS	NM	ZE	PS	NS	NM	P or N	PB
NM	NM	ZE	ZE	NM	NM	P or N	PS

A possible choice of the membership functions for the four mentioned variables of the active suspension system represented by a fuzzy set is as shown in Figure. 5(a) to (d).
The abbreviations used in Table 1 correspond to:

- NV: Negative Very Big
- NB: Negative Big
- NM: Negative Medium
- NS: Negative Small
- ZE: Zero
- PS: Positive Small
- PM: Positive Medium
- PB: Positive Big
- PV: Positive Very Big

The rule base used in the active suspension system can be represented by the following table with fuzzy terms derived by modelling the designer's knowledge and experience. The linguistic control rules of the FLC obtained from the Table used in such a case are as follows:

R_1: IF ($\dot{x}_1 - \dot{x}_2$ =PM) AND ($\dot{x}_1$=PM) AND ($\ddot{x}_1$=ZE) THEN (u=ZE)

R_2: IF ($\dot{x}_1 - \dot{x}_2$ =PS) AND ($\dot{x}_1$=PM) AND ($\ddot{x}_1$=ZE) THEN (u=NS)

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R_{75}: IF ($\dot{x}_1 - \dot{x}_2$ =NM) AND ($\dot{x}_1$=NM) AND ($\ddot{x}_1$=P) THEN (u=PS)

Thus the rules of the controller have the general form of:

R_i: IF ($\dot{x}_1 - \dot{x}_2 = A_i$) AND ($\dot{x}_1 = B_i$) AND ($\ddot{x}_1 = C_i$) THEN ($u = D_i$)

where A_i, B_i, C_i and D_i are the labels of fuzzy sets representing the linguistic values of $\dot{x}_1 - \dot{x}_2$, $\dot{x}_1$, $\ddot{x}_1$ and u, respectively, and characterised by their membership functions.

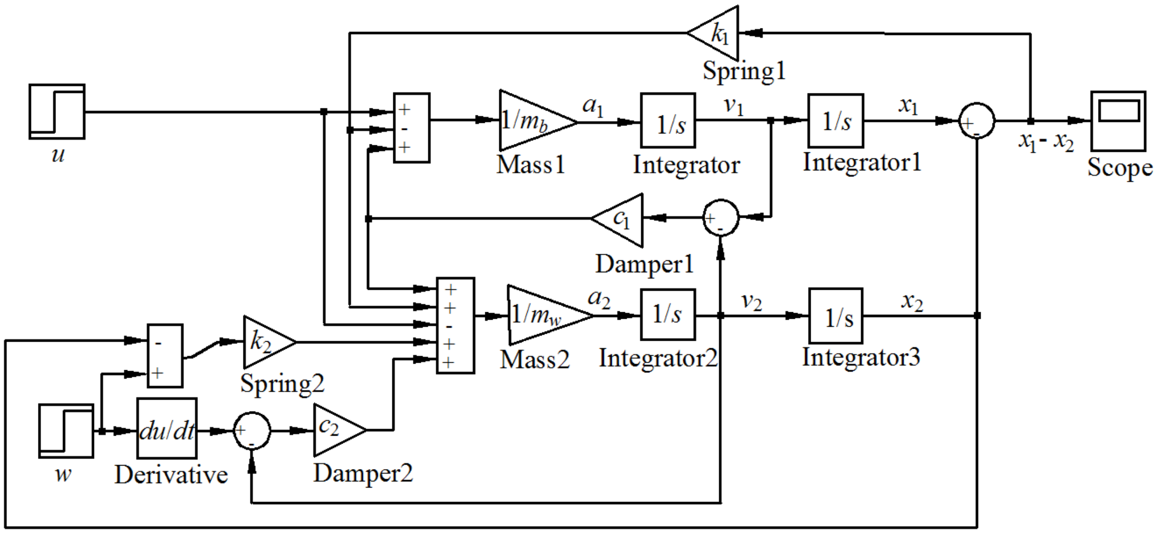

Fig. 4. Simulink model belonging to car suspension system

The output of the fuzzy controller is a fuzzy set of control. In this study, for the process which usually requires a non-fuzzy value of control, a method of defuzzification called “center of gravity method” is used.

5. Determination of the membership function boundaries by genetic algorithms

Genetic algorithms (GAs) are randomized search techniques guided by the principles of evoluation and natural genetics. They are effective, adaptive and robust search procedures, producing near global optimal solutions and having a large amount of implicit parallelism. This method has been widely used by researchers and has been succesfully applied to various problems.

The membership functions have an important role in the control by fuzzy logic method. Triangular and trapezoidal types of membership functions are used in this work. From these membership functions, triangular membership function has got three parameters, *a*, *b* and *c* while the parameters *a* and *b* locate the feet of the triangle, parameter *c* locates the peak, as shown in Figure. 6. These three parameters are expressed as the three genes in the GA operations. Membership functions together constitute the chromosomes, and the chromosomes produce the invididuals.

The membership functions for fuzzy logic controller are optimized by using genetic algorithm operations. The boundaries of fuzzy logic membership functions and their parameters are determined by genetic algorithm method. The objective function selected in the suspension systems is body deflection. It is aimed to reduce the maximum value of this deflection. The selection of population and generation numbers as great quantities increases the diversity, but this situation causes more simulation time. Since they give optimum results about diversity and simulation time, 20 and 30 values are taken for population and generation numbers, respectively.

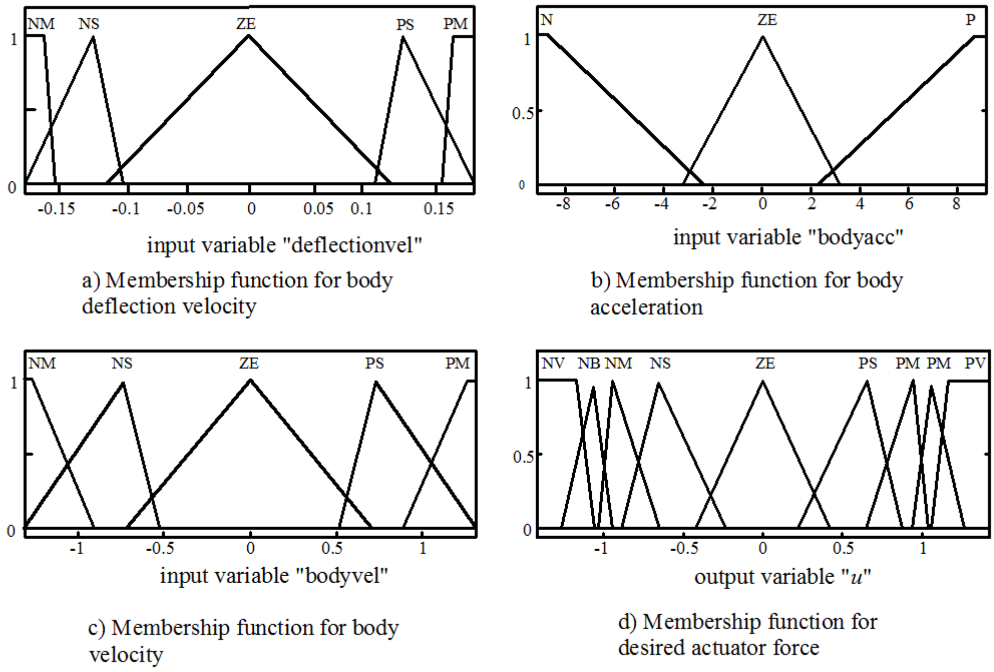

Fig. 5. Membership functions for FLC

As mentioned previously, priorities among the objectives of the FLC optimized by GA can be adjusted by varying boundaries and parameters of membership functions. In order to find the appropriate boundaries and parameters of membership functions that can effectively reduce the maximum body deflections, a series of numerical simulations are conducted with various boundaries of membership functions considering their physical limitations.

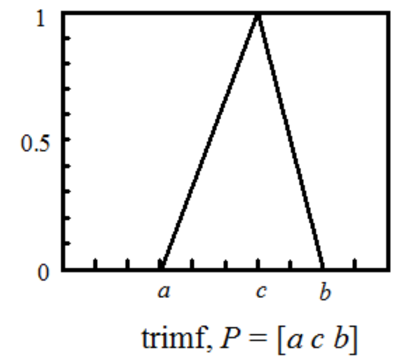

Fig. 6. Triangular type membership function and its parameters

6. Modelling of suspension systems by Simulink

The system shown in Figure 1, is modelled in Simulink by summation of the forces affecting the both masses (body mass and suspension mass) and by taking two successive integrations in Eq. (7) and (8) to obtain the velocities and displacements of each mass. The block diagram of the Simulink computer program implementing the integrations and other mathematical operations is shown in Figure 4.

$$\iint \frac{d^2 x_1}{dt^2} = \int \frac{dx_1}{dt} = x_1 \quad (7)$$

$$\iint \frac{d^2 x_2}{dt^2} = \int \frac{dx_2}{dt} = x_2 \quad (8)$$

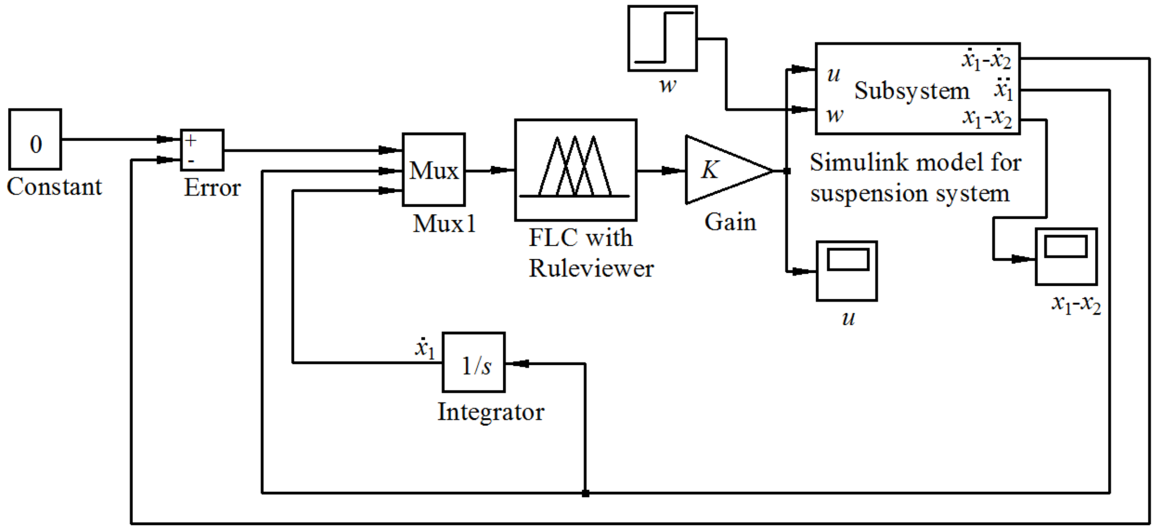

Fig. 7. The block diagram of the FLC model

This Simulink model is used in a FLC model with a feed back control system modelled by the Matlab Fuzzy Logic Toolbox. The block diagram of the FLC model is depicted in Figure 7. In this model, body deflection velocity $\dot{x}_1 - \dot{x}_2$, body velocity $\dot{x}_1$ and body acceleration $\ddot{x}_1$ are taken as the feed back inputs, whereas desired actuator force (u) is the output of the fuzzy logic controller.

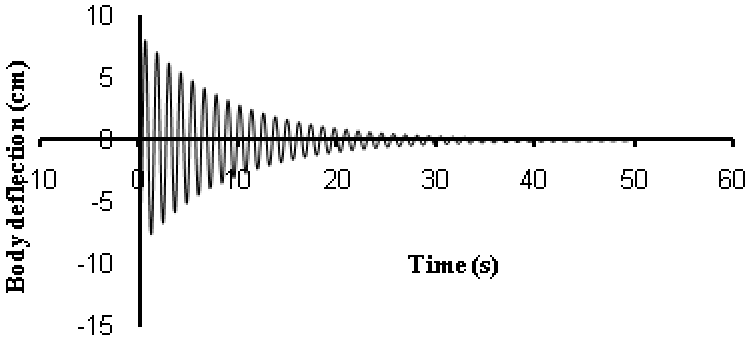

Fig. 8. Output of the not controlled system

The input of the fuzzy logic Simulink model is unit step block which produces 10 cm displacement initially, for road surface roughness. Body deflection which is the output of the model can be traced by means of the scope block until the end of the simulation time.

7. Comparison of simulated PID and FLC controllers

Time versus body deflection relationship of the uncontrolled model is depicted in Figure 8. Since, both the maximum deflection and settle time limits are exceeded, it is clear from the figure that the model does not meet the design requirements.

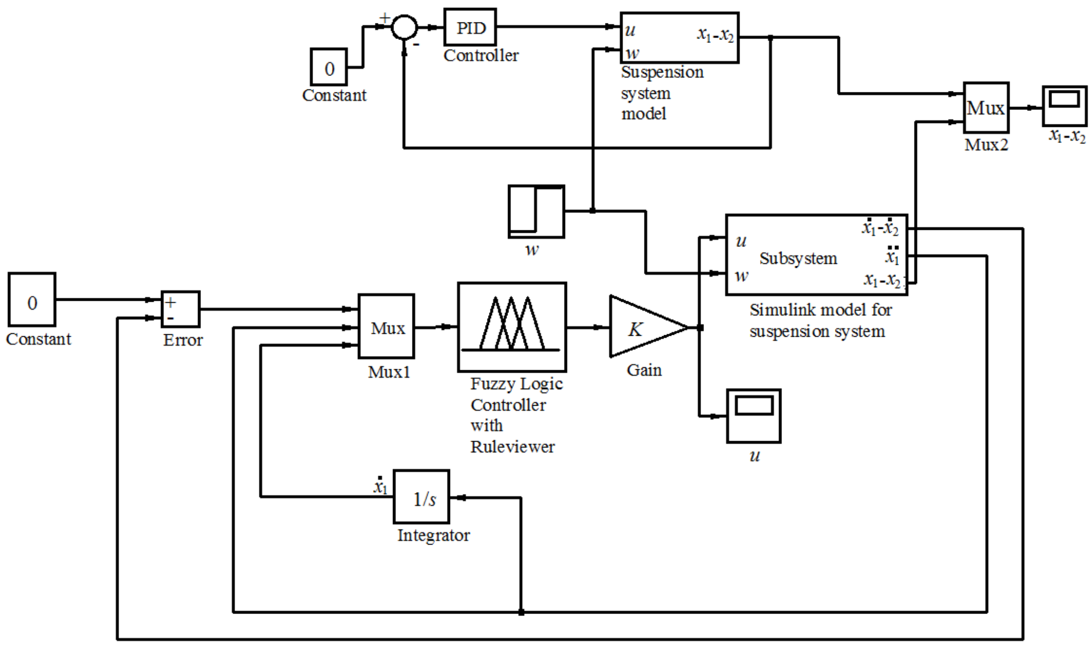

Fig. 9. Simulink model for PID and FLC controllers

Above mentioned PID controller of the suspension system is modelled together with FLC model in Simulink environment, Figure 9. The PID controller block in Figure 9 uses 1664200, 1248150 and 416050 values for K_p, K_I and K_D gains, respectively, as pointed out previously. Thus, two models can be observed simultaneously, and their outputs can be compared by the scope block, easily. These two models have been operated for 5 seconds and their outputs, i.e. body deflections have been compared with each other in Figure 10. It can be seen that the PID controlled suspension system model shows a good performance, because, both the maximum body deflection and the settling time of this system satisfies the design requirements. Moreover, according to the Figure 10, it is obvious that the FLC suspension system model displays smaller deflections than the PID controlled suspension model. This is the superiority of the FLC model to the PID controlled model.

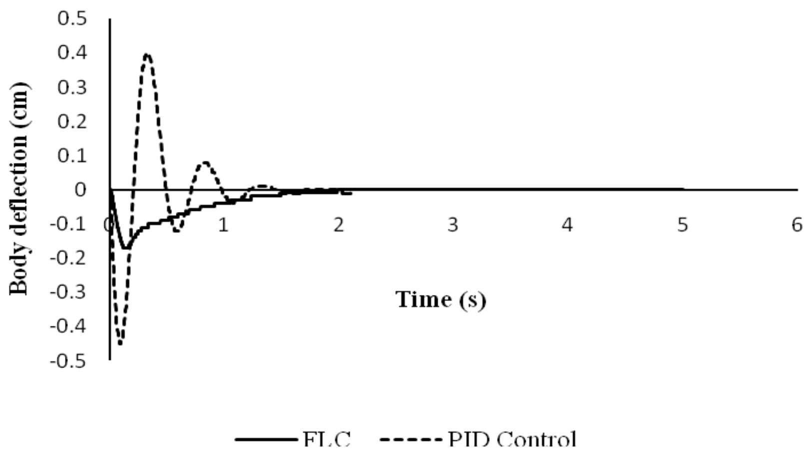

Fig. 10. Comparison of the outputs of PID and FLC controllers

Actuator supplying the control force has a capacity in the range of ± 50 kN. The control forces of the PID and FLC controllers are shown, in Figure 11. From the figure, it is clearly seen that the FLC model is more effective than the PID controlled model. Changing its sign only once and decreasing gradually, the actuator force of the FLC model conveys the system to a stable condition in a more effective manner than the PID model's actuator. And, this is the second advantage of the fuzzy logic controlled model.

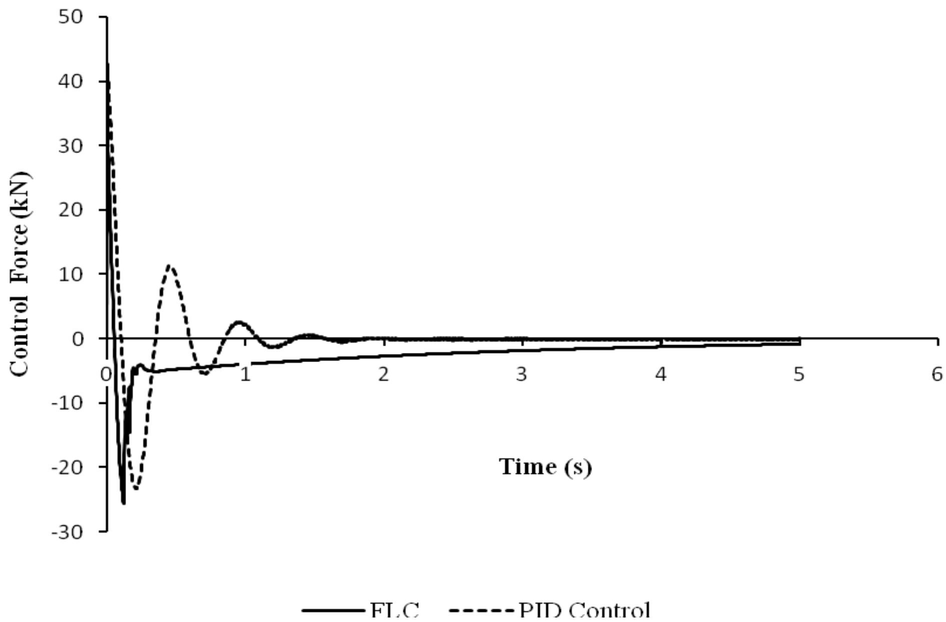

Fig. 11. Comparison of the control forces of PID and FLC controllers

8. Conclusions

A FLC optimized by genetic algorithm for the active suspension of cars has been proposed. The model has been applied to a sample one quarter car model. The results of proposed model are compared with those of PID controller and the efficiency of the FLC controller model has been assessed. It has been shown that the fuzzy-logic controller displays beter performance than the PID controller for both the minimization of the maximum body deflection and the efficiency of the actuator force of the controller.

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