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Active Suspension System Control Using Adaptive Neuro Fuzzy (ANFIS) Controller

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ABSTRACT

The purpose of designing the active suspension systems is providing comfort riding and good handling in different road disturbances. In this paper, a novel control method based on adaptive neuro fuzzy system in active suspension system is proposed. Choosing the proper database to train the ANFIS has an important role in increasing the suspension system's performance. The databaseused to train the proposed ANFIS system is extracted from the outputs of fuzzy, LQR and sliding mode controllers. A quarter-car model is considered to study the performance of the proposed controller. Performance of this controller is compared with the passive system, and active suspension systems with fuzzy and LQR controllers. The results demonstrate that proposed ANFIS controller is better than passive suspension system and active fuzzy and LQR based suspension systems in suspension deflection, body acceleration, settling time and also control force.

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1. INTRODUCTION

The road irregularities cause discomfort riding when driving the vehicle. Vehicle suspension systems have a crucial role in reducing the sprung mass acceleration, providing comfortable and safe riding and suitable suspension deflection to minimize the road damages.

A suspension is normally divided into the following categories depending upon the principle of operating; the passive suspension consists of springs and dampers, the semi-active suspension using a variable damper and the active suspension using hydraulic, air, or electric force actuator. Passive suspension is the simplest to design and economically advantageous[1]. Due to the active suspension advantages such as high control performance in a wide frequency range [2] and generating larger range of force at low velocities [3], many studies have been done on these systems and various models and controlling techniques have been proposed.

Optimal control theory is used to active suspension system control by Thompson [4, 5]. An experimental one degree-of-freedom micro computerized suspension system was designed by Cheok et al. [6]. In the proposed system, the actuator force was used as control input. However, the model which was consideredwas a simple one. Esmailzadeh and Taghirad proposed the optimal state feedback method to control the active suspension systems [7].

To minimize vibration caused by the road unevenness with nonlinear damper, a H_∞ model is proposed by Aubouet, et al.[8]. Nonlinear control method for active suspension systems was designed by Lin and Kanellakopoulos[9]. The robust controlling technique for active suspension systems was proposed by Yahaya et al. [10]. In this method the proportional-integral sliding mode control scheme was used. Kaleemullah and Hasbullah [1] compared three linear controllers like Robust, LQR and fuzzy logic with passive systems. The results showed that these controllers have better performance than passive systems in settling time.

Capability of fuzzy logic in modeling of the systems resulted its application in suspension systems. Many researchers investigated the application of fuzzy logic controllers in vehicles suspension systems. A fuzzy logic suspension controller was proposed by Yoshimura [11]. This method shows more improvement in suspension system as compared with conventional

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controllers. A tunable fuzzy logic controller was designed by Rao et al. [12]. In the proposed controller, the membership function rules were determined by trial and error.

Campos et al. [13] investigated the backstepping based on fuzzy logic control. Their proposed method was a nonlinear method, which is time consuming. Also, implementation of nonlinear control is complex for use in passenger car [14]. Park and Rahmdel[15] developed a fuzzy sliding mode controller based on a variable boundary layer. Their proposed controller is able to remove the chattering, and maintains therobustness of controller simultaneously.

In fuzzy method, there is not a standard algorithm to define the membership functions and control rules. This problem causes the error in control process and decreases the performance of the system. This paper presents a novel ANFIS controller in which thedatabase is created automatically using the outputs of a fuzzy controller, a LQR [1] and a sliding mode controller [10]. Simulation results demonstrate that proposed ANFIS system shows better results with regard to fuzzy active suspension system and passive system.

The paper is organized as follows: Quarter-car model with the state space equations is briefly explained in Section 2. The proposed control scheme is presented in Section 3. The simulation results and their analysis are illustrated and discussed in Section 4. Finally, the paper is concluded in Section 5.

2. QUARTER CAR MODEL

The two DOF (Degree of Freedom) quarter car model considered in this paper is illustrated in Figure 1. m and m_w denote body mass of the car and wheel mass, respectively.

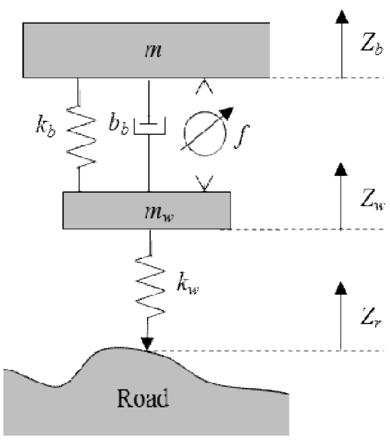

Figure 1. Quarter car suspension model [1]

Quarter-car models are simple and capture many important characteristics of the full model, so they are very often used for suspension analysis and design.

An active suspension system can be modeled by a spring, damper and an actuator between two masses. Considering the physical properties of the wheels, their damping coefficient can be passed up. $k_b$and b_b are suspension stiffness and suspension damping, respectively. k_w is tire stiffness. z_b refers vehicle displacement, z_w refers to wheel displacement and f denotes the actuator which apply the control force. Applying Newton's second law to the tires and body's mass results in the following equations [1, 16]:

$$\ddot{Z}_w = \frac{K_w(Z_w - Z_r)}{m_w} - \frac{K_b(Z_w - Z_b)}{m_w} - \frac{b_b(\dot{Z}_w - \dot{Z}_b)}{m_w} - \frac{f}{m_w} \tag{1}$$

$$\ddot{Z}_b = -\frac{K_b(Z_b - Z_w)}{m} - \frac{b_b(\dot{Z}_b - \dot{Z}_w)}{m} + \frac{f}{m} \tag{2}$$

The above equations could be written in state space form where x_1, x_2, x_3 and x_4 are considered as state variables.x_1 denotes the displacement of the body. x_2 and x_3 refer to the vertical velocity of the body and wheel deflection, respectively. x_4 denotes the vertical velocity of the wheel. Therefore, we have:

$$X = [X_1 \quad X_2 \quad X_3 \quad X_4]^T \tag{3}$$

$$X_1 = Z_b - Z_w \tag{4}$$

$$X_2 = \dot{Z}_b \tag{5}$$

$$X_3 = Z_w - Z_r \tag{6}$$

$$X_4 = \dot{Z}_w \tag{7}$$

Considering these space variables, the state space equations for quarter car model can be written as:Equation (8). These equations are used to design the controllers:

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \\ \dot{X}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & -1 \\ \frac{-K_b}{m_b} & \frac{-b_b}{m_b} & 0 & \frac{b_b}{m_b} \\ 0 & 0 & 0 & 1 \\ \frac{-K_b}{m_w} & \frac{b_b}{m_w} & \frac{K_w}{m_w} & \frac{-b_b}{m_w} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{m_b} \\ 0 \\ \frac{1}{m_w} \end{bmatrix} f + \begin{bmatrix} 0 \\ 0 \\ -1 \\ 0 \end{bmatrix} \dot{Z}_r \tag{8}$$

3. CONTROLLER DESIGN

One of the key points in designing the fuzzy controller is choosing the proper control rules, inputs and membership functions. Any fuzzy logic controller is only as good as the knowledge of the person who designs and implements it. In the proposed system, the vertical displacement and velocity of the suspension system are considered as inputs. These inputs are indicated as follows:

$$FIS\_input_1 = Z_b - Z_w \tag{9}$$

$$FIS\_input_2 = \dot{Z}_b - \dot{Z}_w \tag{10}$$

Bell-shaped membership functions are used to model the inputs and outputs. By choosing these membership functions, each input signal is assigned to all linguistic groups which can reduce the ambiguity in the border areas. Figures2 and 3 show the bell-shaped membership functions chosen for FIS inputs, and Figure 4 shows the bell-shaped membership functions chosen for the output. In these figures NL, NM, NS, Z, PS, PM and PL denote negative large, negative medium, negative small, zero, positive small, positive medium and positive large, respectively. Inputs and output cured face of fuzzy inference is illustrated in Figure 5.The following control rule is applied in fuzzy controller:

If x is A and y is B, then z is C

The total rule base which contains 49 control rules is represented in Table 1. Center of gravity method is used as defuzzification process. So, the control input is determined as Equation (11) in which μi(f) represents the membership functions. The results of this fuzzy controller are used to train the ANFIS system.

$$f = \frac{\sum f_i \times \mu_i(f)}{\sum \mu_i(f)} \tag{11}$$

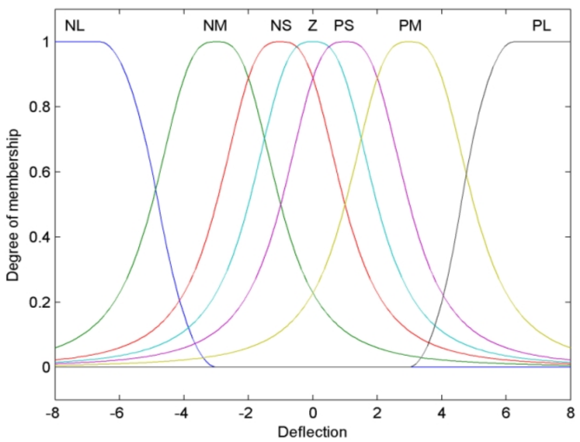

Figure 2. Membership functions for first input (Deflection)

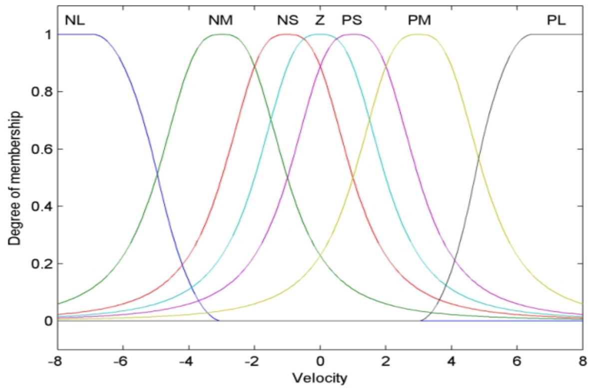

Figure 3. Membership functions for second input (Velocity)

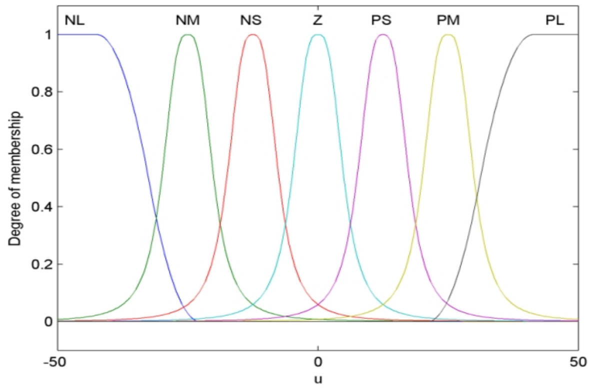

Figure 4. Membership functions for output

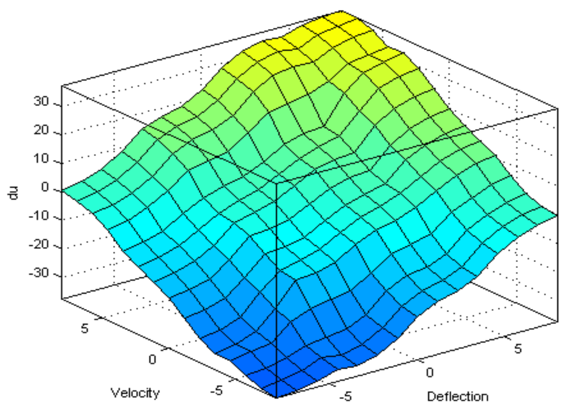

Figure 5. Inputs and output cured face for fuzzy inference

As stated before, in fuzzy method, there is not a standard algorithm to define the membership functions and control rules which cause the error in control process and decrease the performance of the system. One of the remarkable advantages of ANFIS systems is their capability in creating the proper rules and membership functions automatically, based on the input data used for training.

TABLE 1. Total rule base on fuzzy controller

	FIS_input$_1$						
FIS_input$_2$	**NL**	**NM**	**NS**	**Z**	**PS**	**PM**	**PL**
NL	NL	NL	NM	NS	NS	NS	Z
NM	NL	NM	NS	Z	NS	Z	PS
NS	NM	NS	Z	Z	Z	PS	PM
Z	NM	NS	Z	Z	Z	PS	PM
PS	NM	NS	Z	Z	Z	PS	PM
PM	NS	Z	PS	Z	PS	PM	PL
PL	Z	PS	PS	PS	PM	PL	PL

In fact, the ANFIS controller is a method that usesthe knowledge-based and neural learning approach, simultaneously.Because of the linguistic statements from the rule base of the ANFIS controller, the control strategy resembles human thinking process. The ANFIS based controller isexplained in this section which can create the membership functions and rules automatically based on training data. To design an ANFIS controller,an appropriatedatabase is needed.

To create the database, the results of the fuzzy controller proposed in this paper a LQR controller [1] and a sliding mode controller [10] are used. By extracting thedeflection and velocity for each controller and combination of these data, anappropriatedatabase is created. This database is applied to train the ANFIS controller. After training the ANFIs using Hybrid method, ANFIS creates 49 if-then rules.

4. SIMULATIONS AND DISCUSSION

In this section, simulation results are presented for proposed ANFIS based suspension system. For the quarter car model, parameters are considered as follows: m=250kg, m_w=50kg, k_b=16000N/m, k_w=160000N/m and b_b=1500Ns/m. To examine the performance of the system, two types of road disturbances are considered. The first disturbance is a pulse which is defined in Equation (12).

$$Z_r = \begin{cases} 0.1, & 1 < t < 4 \\ 0, & otherwise \end{cases} \qquad (12)$$

Figure 6 shows the suspension systems vertical displacement for different controllers and passive system. It is shown that the ANFIS system has better result compared to other systems. Body velocity and acceleration are shown in Figures 7 and 8, respectively. The results clearly show that the proposed ANFIS system has better performance compared to passive, LQR and fuzzy systems. The velocity and acceleration of the vehicle have reduced in the proposed system, which can provide the comfort riding.

Figure 9 illustrates the control force for different systems. It is quite clear from this figure that the ANFIS controller uses little control force as compared to LQR and fuzzy systems, and it is energy optimal. The second type of disturbance is considered as follows:

$$Z_r = \begin{cases} \frac{0.14(1-\cos(8\pi t))}{2}, & 0.5 < t < 0.75 \\ \frac{0.08(1-\cos(8\pi t))}{2}, & 3.5 < t < 3.75 \\ 0, & otherwise \end{cases} \qquad (13)$$

The simulation results for this disturbance are illustrated in Figures 10, 11, 12 and 13. As it is shown in these figures, the ANFIS system has better performance compared to passive system, fuzzy and LQR systems which can cause good handling for the vehicle. Also, the proposed system has significant reduction in control force as compared with LQR and fuzzy controllers. Figure 14 shows the body displacement for the first road disturbance with different magnitude. It is shown that the ANFIS controller allows a fast rise time and quick settling time without oscillatory behavior. Simulation show that the ANFIS controller givessuitable results for pulse and sinusoidal function road disturbances effectively, and hence it can be said that this controller could handle other real road situations.

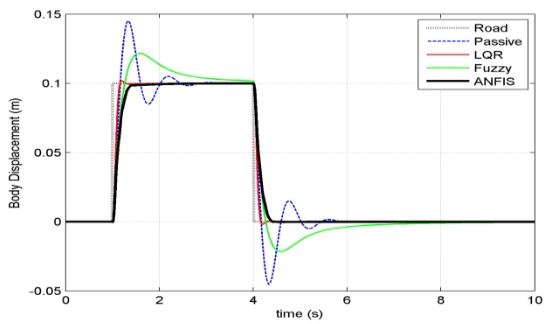

Figure 6. Body displacement for first road disturbance

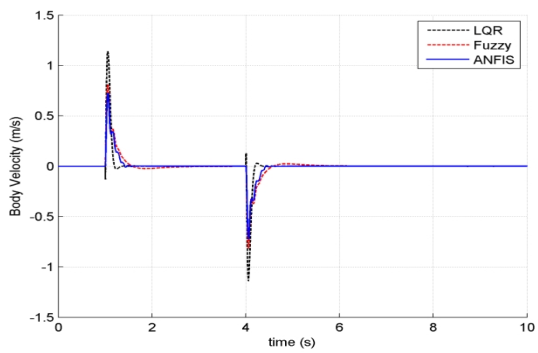

Figure 7. Body velocity for first road disturbance

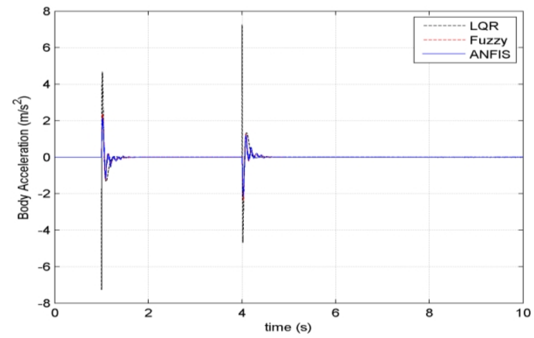

Figure 8. Body acceleration for first road disturbance

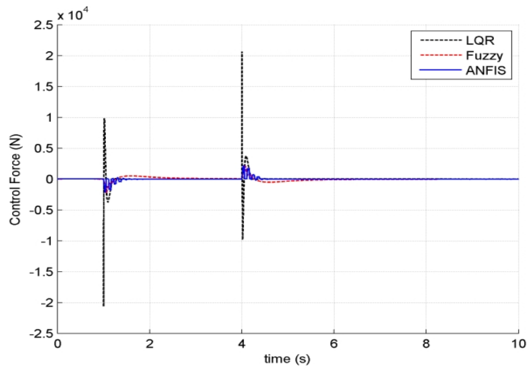

Figure 9. Control force for first road disturbance

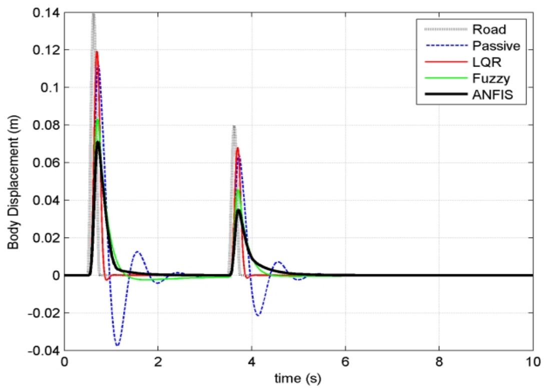

Figure 10. Body displacement for second road disturbance

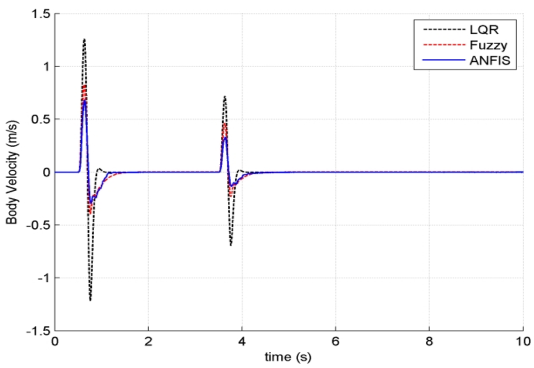

Figure 11. Body velocity for second road disturbance

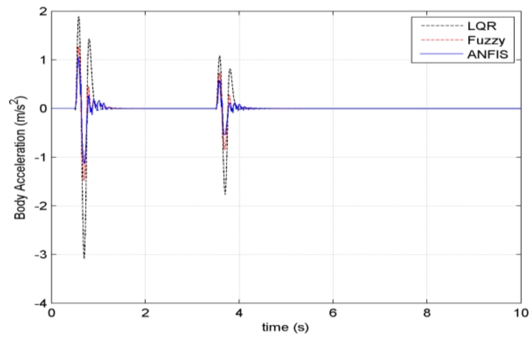

Figure 12. Body acceleration for second road disturbance

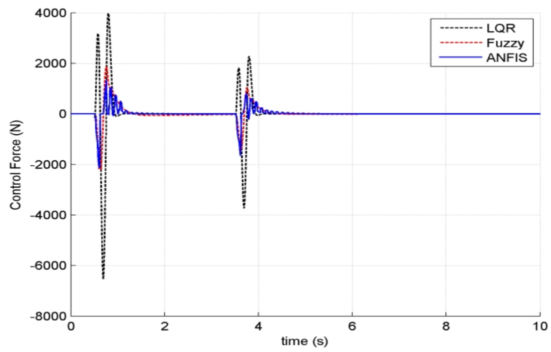

Figure 13. Control force for second road disturbance

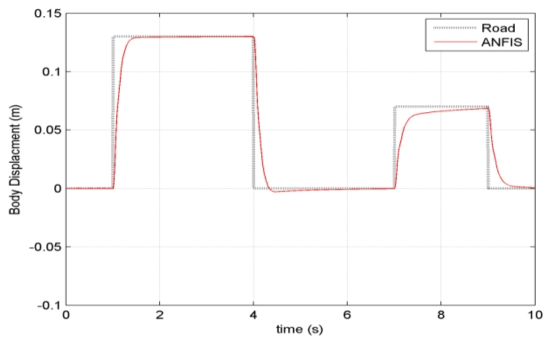

Figure 14. Body displacement for first road disturbance with different magnitude

5. CONCLUSIONS

An active suspension system has been designed based on adaptive neuro fuzzy systems. A proper database which were extracted from fuzzy, LQR and sliding mode controllers were used to train the ANFIS system. Simulations were done for two types of disturbances, and the results were compared with passive, fuzzy and LQR systems. Simulation results demonstrate that proposed ANFIS controller is better than passive suspension system and active suspension with fuzzy and LQR controllers in suspension deflection, body acceleration, settling time and control force. Therefore, it can guarantee a comfort ride and good handling. The discussion about suspension problem in full car model is the subject that authors hope to study in near future using the main concepts of this paper.

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چکیده

هدف از طراحی یک سیستم تعلیق فعال، فراهم نمودن آسایش و راحتی برای راننده و سرنشینان اتومبیل در مواجهه با ناهمواری‌های جاده می‌باشد. در این مقاله روش کنترلی جدیدی بر اساس سیستم استنتاج فازی عصبی تطبیقی برای سیستم تعلیق فعال پیشنهاد می‌شود. تهیه و انتخاب پایگاه داده‌ی مناسب برای آموزش ANFIS نقش مهمی را در افزایش کارایی سیستم ایفا می‌کند. پایگاه داده‌ی مورد استفاده، از خروجی کنترلرهایفازی، LQR و مدلغزشی تهیه شده است. یک مدل ربع خودرو برای شبیه‌سازی و بررسی کارایی سیستم پیشنهادی، درنظر گرفته شده است. عملکرد سیستم پیشنهادی با عملکرد سیستم غیرفعال و سیستم‌های فعال با کنترل کننده‌هایفازی و LQR مقایسه شده است. نتایج شبیه‌سلزی‌ها نشان می‌دهد که کنترلرANFIS طراحی شده از لحاظ جابجایی بدنه، شتاب بدنه، زمان نشست و نیروی کنترلی، بهتر از سیستم‌های پیشین می-باشد.

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