ANFIS Control of Vehicle Active Suspension System

Narinder Singh Bhangal and Shailendra Chaudhary
Instrumentation and Control Engg., Dr. B.R. Ambedkar National Institute of Tech., Jalandhar, India
Email: nsbhangal@yahoo.co.in, Shailendrachaudhary2512@gmail.com

***Abstract*—Suspension in a vehicle is provided primarily to improve the passenger comfort and road handling in different road conditions. Active suspension is proven to be better than a passive suspension system. In this paper, a quarter car model is considered to study the performance of the proposed controller. Choosing the proper database to train an adaptive neural fuzzy inference(ANFIS) plays an important role in improving the suspension system performance. The database used to train the proposed ANFIS controller was extracted from a linear quadratic regulator (LQR) controller. The purpose of this paper is to investigate the performance of an active suspension system using ANFIS and LQR controllers. MATLAB/SIMULINK was used to study the simulation of vehicle's performance on a road. The results show that both LQR and ANFIS controllers can effectively control the vertical vibration of the vehicle as compared to passive suspension system. Moreover the ANFIS control method is found to be more effective in reducing the acceleration of a sprung mass as compared to LQR control.**

***Index Terms*—Vehicle Active Suspension System (VASS), Fuzzy Logic Controller (FLC), Linear Quadratic Regulator (LQR)**

I. Introduction

A car suspension system is the mechanism that physically isolates the car body from the wheels of the car. The purpose of the suspension system is to provide a smooth ride and to help maintain control of the vehicle over rough terrain. Ride comfort and road handling determine the performance of the suspension system. Ride comfort can be measured by observing the body's vertical acceleration and road handling can be observed by suspension deflection. Suspension systems can be classified into three categories passive, semi active and active suspensions. Passive suspension has the ability to store energy via a spring and dissipate it via a damper [1]. Passive suspensions can only achieve good ride comfort or good road handling since these two criteria conflict with each other and involve different spring and damper characteristics.Semi-active suspensions with their variable damping characteristics and low power consumption, offer a considerable improvement.

A significant improvement can be achieved by using an active suspension system. Active suspension can give better performance by using a force actuator. The force actuator is a mechanical device that is added to the system and governed by a controller. The controller will calculate whether to either add or dissipate energy from the suspension system with the help of sensors.

A lot has been reported in the literature on the control strategies for an active suspension system. A linear quadratic regulator (LQR) and fuzzy logic controllers (FLC) are popular controllers used to improve the ride comfort and road handling. A comparison between passive and active suspension systems was performed by using different types of road profiles for a quarter car model, in which a LQR control is found to be better than a passive system in suppressing the vibrations [2][3]. Previous studies have made full use of the advantages of neural network and fuzzy logic controllers. However, only a few researches have made use of a combination of the two techniques to solve the suspension problem. A neuro fuzzy model that combines the features of a neural network and a fuzzy logic model is called an Adaptive Network based Fuzzy Inference System(ANFIS). An ANFIS system is more efficient and more powerful than either the neural network or fuzzy logic system [4][5][6]. The performance of an ANFIS controller based system is compared with passive, fuzzy and LQR based suspension systems. The results show that the performance of the ANFIS based system is much better than the other systems [7][8]. Based on simulations, it can be concluded that the neuro fuzzy controller performs well both in terms of passenger comfort and vehicle handling in comparison to the passive, LQR, and fuzzy based systems [9][10].

The aim of this paper is to present an ANFIS based active suspension system that improves the passenger ride comfort and road handling in a quarter car model. A comparison of body displacement, body acceleration and suspension deflection using ANFIS and a LQR control has been made.

II. Mathematical Modeling

Fig. 1 shows the quarter vehicle model for an active suspension system. The sprung mass m_b represents the mass of the vehicle body, frame and internal components that are supported by the suspension. The unsprung mass ,m_w is the mass of the assembly of the axle and wheel. k_S and b_S are the spring and damper coefficients of the passive component respectively. Tyre

Manuscript received February 7, 2018; revised July 1, 2018.

doi: 10.18178/ijmerr.7.4.433-437

compressibility is K_t. The control force generated by the actuator is f_S and r denotes the road disturbance input acting on the unsprung mass.

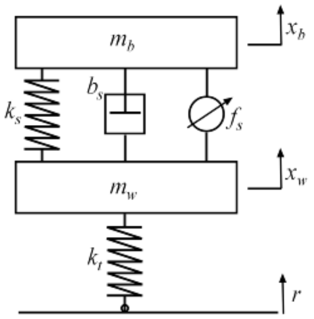

Figure 1. Quarter vehicle model of active suspension system

The vertical displacements of the sprung and unsprung masses are denoted as x_b and x_w respectively. Table I shows the parameters of quarter active suspension system.

TABLE I. PARAMETERS OF THE QUARTER VEHICLE MODEL

Model parameters	symbol	Values
Vehicle body mass	m_b	300kg
Wheel assembly mass	m_w	60kg
Suspension stiffness	k_s	1600N/m
Suspension damping	b_s	1000N-s/m
Tyre stiffness	k_t	190000N/m

To develop the state space model of the system, the state variable are defined as $x_1 = x_b$, $x_2 = x_w$, $x_3 = \dot{x}_b$, $x_4 = \dot{x}_w$

The equation of motion of the system for sprung and unsprung masses are as follow

$$m_b \ddot{x}_b = k_s (x_w - x_b) + b_s (\dot{x}_w - \dot{x}_b) + f_s \quad (1)$$

$$m_w \ddot{x}_w = k_t (r - x_w) - k_s (x_w - x_b) - b_s (\dot{x}_w - \dot{x}_b) + f_s \quad (2)$$

The dynamics of the system is described by the following
state space model. State space representation is given by

$$\dot{X} = AX + Bf_S + Fr \quad (3)$$

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{k_s}{m_b} & \frac{k_s}{m_b} & -\frac{b_s}{m_b} & \frac{b_s}{m_b} \\ \frac{k_s}{m_w} & -\frac{(k_s+k_t)}{m_w} & \frac{b_s}{m_w} & -\frac{b_s}{m_w} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{k_t}{m_w} \end{bmatrix} r + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{m_w} \\ -\frac{1}{m_w} \end{bmatrix} f_s$$

The output variables are
$x_b = x_1$ = Car Body displacement
$a_b = \ddot{x}_1$ = Car Body Acceleration
$s_d = x_b - x_w$ = Suspension deflection

III. CONTROLLER DESIGN

In this paper, two types of controller are studied for an active suspension system. These are the linear quadratic regulator (LQR) and the adaptive neuro-fuzzy inference (ANFIS) controller.

A. *Linear Quadratic Regulator (LQR) Controller*

The statement of optimal control is to find an optimal control vector $u^*(t)$ that minimizes a quadratic cost function that consists of a state vector and a control vector. The cost function is denoted as

$$J = \int_0^\infty \left[X' Q X + U' R U \right] dt \quad (4)$$

Where X is the state vector and U is the control vector.
A positive semi definite solution exists under certain conditions yielding a control vector U (t) given by

$$U^*(t) = KX(t) \quad (5)$$

where K is the feedback gain matrix defined by

$$K = -R^{-1} B^T P X \quad (6)$$

where P is solution to the Riccati equation

$$PA + A^T P - PBR^{-1} B^T P + Q = 0 \quad (7)$$

Fig. 2 shows the state variable feedback configuration

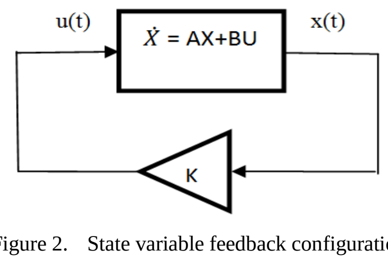

Figure 2. State variable feedback configuration

The main problem of linear optimal control is how to select the matrices Q and R to meet the desired response of the control system. Closed loop responses will change depending on the choice of the Q and R matrices. Generally speaking selecting Q large means that, to keep J small, the state x(t) must be small. On the other hand, selecting R large means that, the control input u(t) must be small, to keep J small. If we want a fast response, Q should be large and R small. For a slow response, Q should be low and R high. One should select Q to be a positive semi definite and R to be a positive definite.

The feedback gain matrix (K) is determined by using control system toolbox and is given by

K= [0.2846; -20.4494; 0.9726; -0.8260]

Fig. 3 shows the Simulink model of the LQR controller based control system.

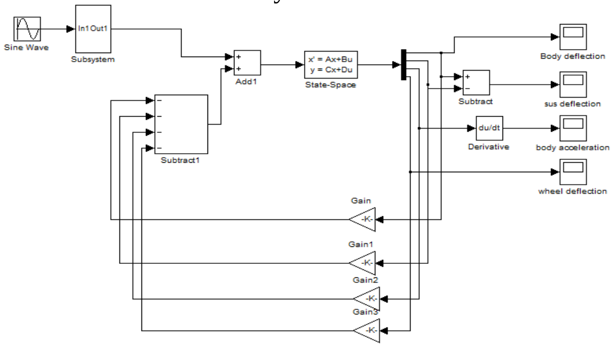

Figure 3. The LQR controller based active suspension system

B. ANFIS Architecture

Assuming the fuzzy inference system has two inputs x and y and one output z, the Sugeno fuzzy model with two fuzzy if-then rules can be expressed as

Rule 1 : If x is A_1 and y is B_1 then $f_1 = p_1 x + q_1 y + r_1$

Rule 2 : If x is A_2 and y is B_2 then $f_2 = p_2 x + q_2 y + r_2$

Fig. 4 shows the reasoning mechanism for this Sugeno model.

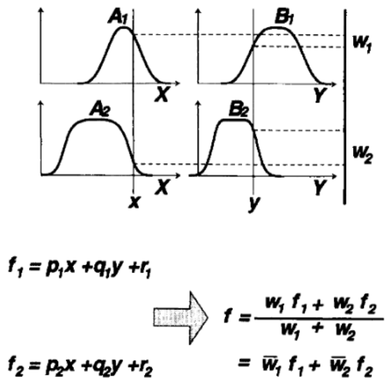

Figure 4. The two input Sugeno fuzzy model

Fig. 5 shows the corresponding equivalent ANFIS architecture.

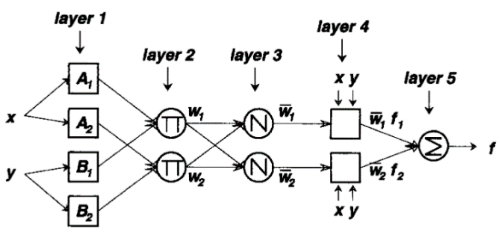

Figure 5. Equivalent ANFIS architecture

C. State Variable Fusion

The system has four state variables, where X = ($x_b, x_w, \dot{x}_b, \dot{x}_w$). If we use the normal fuzzy control method, taking 5 membership functions for each state variable, then the number of rules is equal to 5^4. This can cause "rule explosion". To solve this problem, the optimal control theory and the fuzzy control strategy are combined. We transform variables into an error 'E' and the rate of change of error 'EC', which removes the problem of rule explosion.

In a LQR based controller design, where K is given by K = [k_1 k_2 k_3 k_4] the active suspension system fusion matrix is given as

$$F = \begin{bmatrix} k_1 & k_2 & 0 & 0 \\ 0 & 0 & k_3 & k_4 \end{bmatrix}$$

Hence the error 'E' and rate of change of error 'EC' can be given as:

$$\begin{bmatrix} \mathrm{E} \\ \mathrm{EC} \end{bmatrix} = \mathrm{F} * \mathrm{X}'$$

D. ANFIS Controller Design

The Anfis controller design is based on LQR controller system data, therefore the input and state variable data are obtained from LQR based control system. From this the variables E and EC are calculated using the fusion function. Finally, as Fig. 6 shows, the data is loaded into the ANFIS editor GUI.

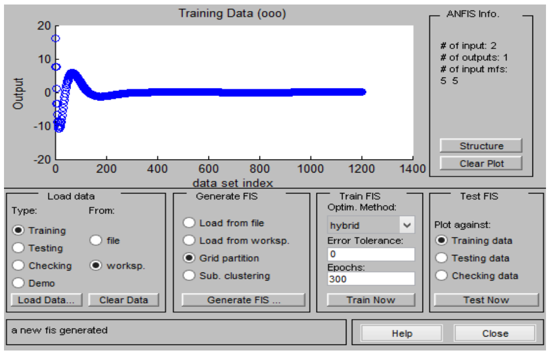

Figure 6. . Loaded training data plot in the ANFIS editor

The acquired dynamic data is considered as a group training data for the ANFIS controller. A FIS file is generated in the GUI having five Gaussian membership functions for each input and output. Finally, we train the FIS file with hydrid optimization taking zero tolerance error and 300 epochs. As Fig. 7 shows, the training error comes out to be 0.0303.

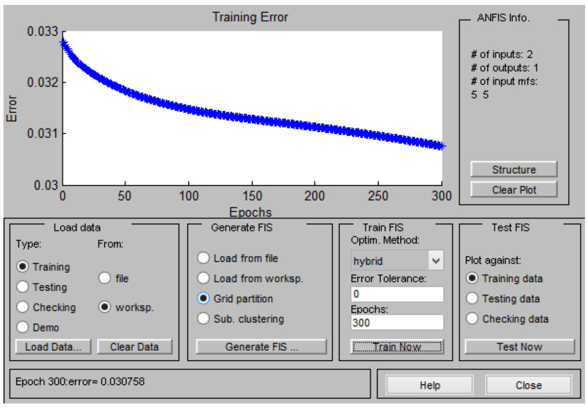

Figure 7. Training error plot and training error

Fig. 8 shows the final ANFIS structure.

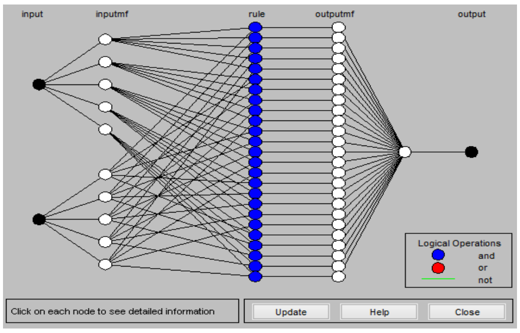

Figure 8. ANFIS network structure

Fig. 9 shows the ANFIS control structure in Simulink.

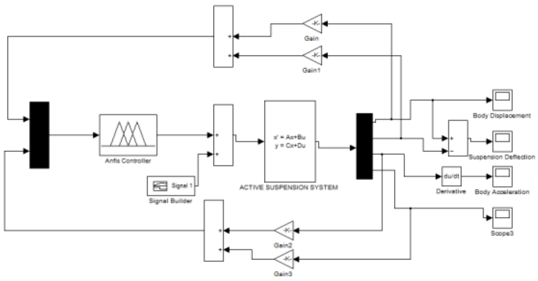

Figure 9. ANFIS control structure

IV. Simulation and Results

To investigate the suspension performance, a perfect road surface model is necessary. In this study, the signal used to simulate the road disturbance is shown in Fig. 10.

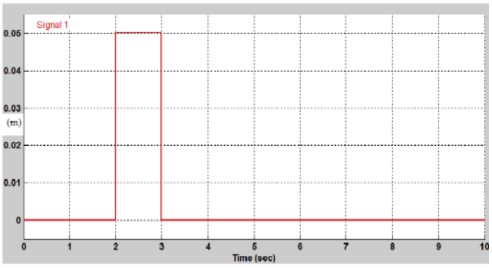

Figure 10. Road Disturbance

Figs. 11, 12 and 13 show the simulation results, which compare the LQR and ANFIS controlled systems by body deflection, suspension deflection and body acceleration with road disturbance. They show that there is an improvement in the ride comfort performance and suppression of vibrations when using ANFIS control as compared to the LQR based systems.

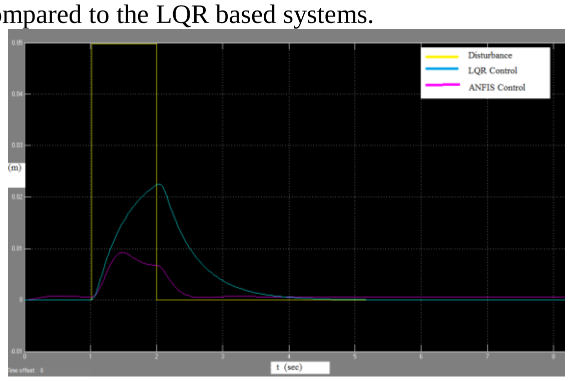

Figure 11. Body deflection

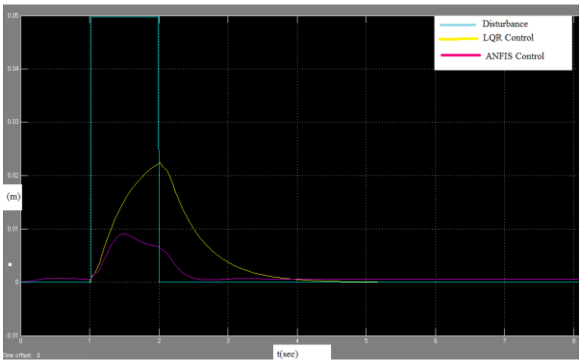

Figure 12. Suspension deflection

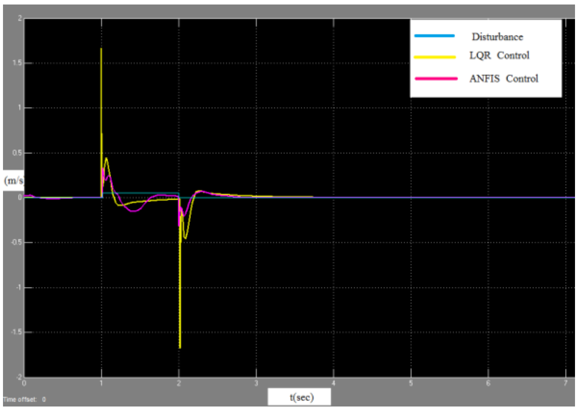

Figure 13. Body acceleration

Tables II, III and IV compare LQR and ANFIS based suspension systems in terms of settling time and percentage overshoot in body deflection, suspension deflection and body acceleration.

As Table II shows in comparison with the LQR controller, the ANFIS controller gives a percentage reduction in settling time and % overshoot in body displacement of 37.5% and 55.5% respectively. As Table III shows, the reduction in settling time and % overshoot in suspension deflection are 37.5% and 59% respectively. As Table IV shows, the percentage reduction in settling time and % overshoot in body acceleration are 25% and 80% respectively.

TABLE II. Comparison of Body Displacement

Time Domain Specification	LQR controller	ANFIS controller
Settling Time(sec)	4.0	2.5
%Overshoot	45	20
Steady state error	0	0

TABLE III. Comparison of Suspension Deflection

Time Domain Specification	LQR controller	ANFIS controller
Settling Time(sec)	4.0	2.5
%Overshoot	44	18
Steady state error	0	0

TABLE IV. COMPARISON OF BODY ACCELERATION

Time Domain Specification	LQR controller	ANFIS controller
Settling Time(sec)	2	1.5
%Overshoot	3000	600
Steady state error	0	0

V. CONCLUSION

In this paper, ANFIS based controlled and linear quadratic regulator based controlled systems were successfully designed using MATLAB for a quarter car active suspension system. As compared to a passive suspension system, both of the controllers are capable of stabilizing the suspension system very effectively, however the suppression of vibration is more effective with ANFIS controller based system as compared to the LQR controller based system. The percentage reduction in settling time and overshoot in suspension deflection and body acceleration of the vehicle suspension system is much improved with the ANFIS controller.

REFERENCES

[1] A. Aly and F. A. Salem, "Vehicle suspension system control: A review, "*International Journal of Control, Automation and Systems*, vol.2, no 2, July 2013, pp. 46-54.

[2] A. Agharkakli, G. S. Sabet, and A. Baronz, "Simulation and analysis of passive and active suspension system using quarter Car model for different road conditions," *International Journal of Eng. Trends and Technology*, vol 3, no. 5, 2012, pp. 636-644.

[3] Y. Qin, M. Dong, F. Zhao, and R. Langari, "Road profile classification for vehicle semi active suspension system based on adaptive neuro fuzzy inference system," *IEEE 54th Annual Conference on Decision and Control*, Dec 15-18, 2015, Osaka, Japan

[4] F. Zhao, S. Samge, F. Tu, and Y. Qin, "Adaptive neural network control for active suspension system with actuator saturation," *IET Control Theory Appl*., vol.10, no. 14, pp. 1696-1705, 2016.

[5] J. S. R. Jang, C. T. Sun, and E. Mizutani, "Neuro fuzzy and soft computing," Prentice Hall, Upper South River ,1997.

[6] J. S. R. Jang and C. T. Sun, "Neuro- fuzzy modeling and control," *Proceedings of the IEEE*, vol. 83, no. 3, pp. 378-406, 1995.

[7] H. Moghadam-Farad and F. Samadi, "Active suspension control system using adaptive neuro fuzzy controller," *International Journal of Engineering*, vol. 28, no. 3, March, 2015, pp. 396-401.

[8] R. Kalaivani and P. Lakshmi, "Adaptive neuro fuzzy controller for vehicle suspension system," in *Proc. Fifth International Conference on Advanced Computing*, 2013, pp. 236-240.

[9] Z. Guosheng, Ye Song, Z. Xia, and P. J. Yi, "The research of automobile suspension system performance based on fuzzy neural network control," *IEEE Transportation Electrification Conf. and Expo*. Asia Pacific, 31Aug.-3 Sept., 2014, Beijing, China.

[10] J. W. Li, H. Y. Shan, and H. Sun, "The design of neuro fuzzy controller for active suspension system," *Applied Mechanics and Materials*, vol. 330, 2013, pp 673-676 .

Narinder Singh Bhangal recevied his B.Tech in Electrical Eng. from Punjab University, Chandigarh, India in1984 and his M.Tech in control systems from Punjab Agricultural University, Ludhiana, Punjab, India.He is currently working as an Associate Professor at Dr. BR Ambedkar National Institute of Technology, Jalandhar, Punjab. His area of research is optimal control, fuzzy, neuro-fuzzy control and robust control of single link flexible , two link rigid manipulators and vehicle active suspension system Email : nsbhangal@yahoo.co.in