World Academy of Science, Engineering and Technology
International Journal of Computer and Systems Engineering
Vol:11, No:5, 2017

Self-Tuning Fuzzy Control of Seat Vibrations of Active Quarter Car Model

Devdutt

Abstract**—**An active quarter car model with three degrees of freedom is presented for vibration reduction of passenger seat. The designed Fuzzy Logic Controller (FLC) and Self-Tuning Fuzzy Logic Controller (STFLC) are applied in seat suspension. Vibration control performance of active and passive quarter car systems are determined using simulation work. Simulation results in terms of passenger seat acceleration and displacement responses are compared for controlled and uncontrolled cases. Simulation results showed the improved results of both FLC and STFLC controllers in improving passenger ride comfort compared to uncontrolled case. Furthermore, the best performance in simulation studies is achieved by STFLC controlled suspension system compared to FLC controlled and uncontrolled cases.

Keywords**—**Active suspension system, quarter car model, passenger ride comfort, self-tuning fuzzy logic controller.

I. Introduction

SUSPENSION system affects the ride comfort and safety of travelling passengers. The design and development of vehicles to provide improved ride quality is a challenging task in automotive sector. Passive suspension system provides limited performance in terms of ride comfort and vehicle handling matters compared to semi-active and active suspension systems [1], [2]. The active and semi-active suspension systems can deliver desired results in vibration suppression due to application of latest control system technology in vehicles. These electronically controlled suspension systems are assembled with actuators and sensors. Thus, varying control force can be supplied in suspension system by these mechatronics based devices depending upon the intensity of vibrations transferred in vertical direction from road surface. Active suspension systems provide better ride quality and road holding ability compared to passive and semi-active suspension system technology [3]. Due to latest development and innovations in active suspension system technology, automotive industries have high interest in this growing field, which can fulfill customer expectations regarding ride comfort issues.

In past, various experimental and simulation based studies have been carried out using different controllers in active quarter car model. Fialho and Balas [4] used the adaptation factor where linear parameter-varying techniques were used in combination with nonlinear backstepping to design lower and higher level control for active quarter car suspension model. Huang and Lin [5] proposed on-line learning based neural network control in combination with sliding mode control for use in active quarter car suspension system. Lauwerys et al. [6] applied frequency domain identification method in combination with μ-synthesis scheme for controller design in active quarter car suspension. Huang and Chen [7] used adaptive sliding controller in active quarter car system to control the sprung mass oscillation for input road profile variations. Here, a fuzzy scheme having the online learning ability was introduced for improving the controller performance. Rajeswari and Lakshmi [8] presented the distance based Fuzzy Sliding Mode Controller with Genetic Algorithm to tune the Fuzzy gain parameters in active quarter car model. Shirjoposht et al. [9] applied optimal law using Extended Kalman Filter (EKF) filter in suspension system of an active quarter car model. Gao and Kaynak [10] improved ride comfort in active quarter car model with the application of Kalman-Yakubovich-Popov (KYP) lemma. The feedback controller was designed using linear matrix inequality method. Guon and Zhang [11] used active quarter car model with two degrees of freedom having robust HN control and linear matrix inequality optimization to study the active suspension control for non-stationary running stage. Lian [12] proposed an enhanced adaptive self-organizing fuzzy sliding mode controller (EASFSC) in active quarter car suspension system. The improved control performance of EASFSC compared to active suspension system with SOFC was shown by experimental results. Deshpande et al. [13] developed a novel scheme in combination with sliding mode control to control the sprung mass acceleration to study the effects of nonlinear spring, damper, load variation and road disturbance parameters. Moghadam-Fard and Samadi [14] designed an active quarter car suspension system with adaptive neuro fuzzy controller. The simulation results demonstrated the better performance of proposed ANFIS controller in vibration suppression of body acceleration and settling time compared to uncontrolled, fuzzy and LQR controlled suspension systems.

It can be seen from above literature review that active quarter car model with two degrees of freedom has been selected for vibration control of sprung mass. Furthermore, some studies have been conducted using quarter car model to improve the ride comfort of travelling passengers with various control strategies [15]-[17]. In this context, a quarter car model with three degrees of freedom having passenger seat is presented to study ride comfort issues under road excitation condition. The main objective of present research work is to study the vibration response of passenger seat under bump road excitation. A quarter car model with three degrees of

Dr. Devdutt is Associate Professor in Mechanical Engineering Department, Manav Rachna International University, Faridabad, Haryana, India (e-mail: devdutt.ymca@gmail.com).

freedom is designed for uncontrolled and controlled suspension systems. For controlling purpose, FLC and STFLC are designed. The simulation results of passive and active quarter car models of passenger seat in terms of vertical acceleration and displacement response are compared with each other. The best performance for the STFLC is achieved in simulation work to achieve desired ride comfort of travelling passengers compared to passive and fuzzy logic controlled suspension systems.

II. Quarter Car System

The active quarter car model with three degrees of freedom is shown in Fig. 1. It can rapidly show the performance of suspension system compared to complicated full car model. The model is designed with following parameters, m_P is the passenger seat mass, m_s is the sprung mass and m_u is unsprung mass respectively; c_P, c_s, k_P and k_s are damping coefficient and spring stiffness of passenger seat and main suspension respectively; k_t represents tyre stiffness. F_a is input control force in passenger seat suspension; x_P, x_s and x_{us} are displacements of the considered masses while x_r is the supplied input road excitations to the quarter car model.

The mathematical equations of the active quarter car model with three-degrees-of-freedom taking passenger seat dynamics is derived using Newton's 2nd Law of Motion as:

$$m_P\ddot{x}_P + c_P(\dot{x}_P - \dot{x}_s) + k_P(x_P - x_s) + F_a = 0 \quad (1)$$

$$m_s\ddot{x}_s - c_P(\dot{x}_P - \dot{x}_s) - k_P(x_P - x_s) + c_s(\dot{x}_s - \dot{x}_{us}) + k_s(x_s - x_{us}) - F_a = 0 \quad (2)$$

$$m_{us}\ddot{x}_{us} - c_s(\dot{x}_s - \dot{x}_{us}) - k_s(x_s - x_{us}) + k_t(x_{us} - x_r) = 0 \quad (3)$$

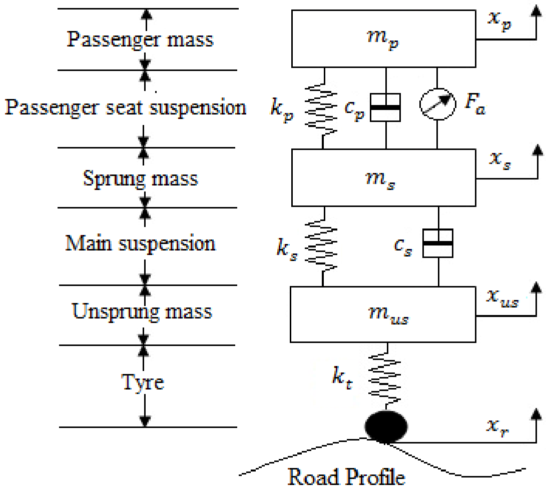

Fig. 1 Active quarter car suspension system

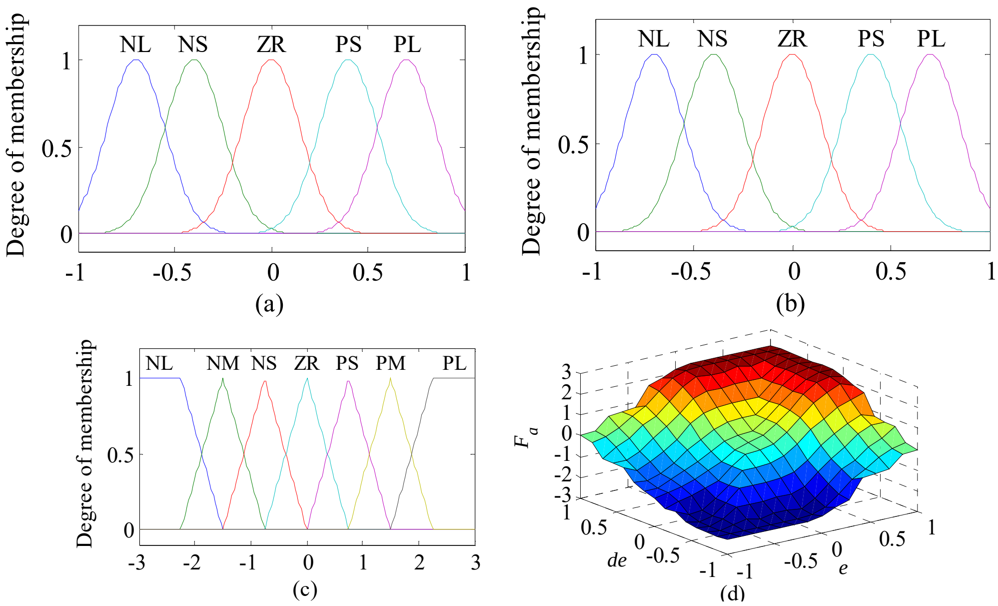

Fig. 2 MFs for FLC (a) Input variable, e ; (b) Input variable, de; (c) Output variable, F_a; (d) Surface plot

III. Controller Design

In this research work, the aim is to control the passenger seat vibrations to enhance passenger ride comfort during vehicle running period. To achieve the desired aim, application of two control strategies are studied in vehicle suspension system. The applied control strategies include FLC controller and STFLC controller respectively.

A. FLC

The structure of designed FLC with two input signals as error (e) and error change (de) and one output signal as supplied damping force (F_a) is shown in Fig. 3. The used linguistic variables are as: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big) respectively. The input and output membership shapes are defined in the interval of [-1, 1] and [-3, 3] respectively. Fig. 2 shows the membership functions as well as surface plot for the designed fuzzy controller. The actual interval of variables is generated during working period of controller as per selected magnitude of input scaling factors S_e, S_{de} and output scaling factor as S_u.

The written fuzzy rules can be studied as: IF $e = E_i$ and $de = dE_j$ THEN $U = U_{(i,j)}$. The rules for integrated fuzzy controller are developed based on the behavior of vibrating suspension system during working period. The fuzzy rule table defining relationship between supplied input signal and output signal to be generated is shown in Table I. Mamdani method is applied for fuzzification while centroid method is used for defuzzification work to obtain numerical data from linguistic variables.

TABLE I
Rule Base for Computing F_A

de/e	NL	NS	ZR	PS	PL
NL	NL	NL	NM	NM	ZR
NS	NL	NS	NS	ZR	PM
ZR	NL	NS	ZR	PS	PL
PS	NM	ZR	PS	PS	PL
PL	ZR	PM	PL	PL	PL

B. STFLC

The STFLC controller is designed to enhance the overall controller performance automatically in vibration control applications without human intervention by tuning the output scaling factor of the main fuzzy controller. The structure of STFLC is the combination of normal fuzzy controller and gain tuning fuzzy controller as shown in Fig. 3.

It is supplied with two inputs de_N and e_N and provide output signal as gain updating factor (k). The gain updating factor (k) is supplied based on the written fuzzy rules of the form:

Rule : If e is E and Δe is ΔE then k is k.

The updating factor's membership function for input are defined in range of [-1, 1] while for the output in domain [0, 1] and shown in Fig. 4. The rule base for computing the value of k is shown in Table II.

TABLE II
Rule Base for Computing k

de/e	NL	NS	ZR	PS	PL
NL	PL	PL	PL	PM	ZR
NS	PL	PS	PS	ZR	PM
ZR	PL	PS	ZR	PS	PL
PS	PM	ZR	PS	PS	PL
PL	ZR	PM	PL	PL	PL

IV. Simulations Results

In this section, simulation work is performed using quarter car model with three degrees of freedom for comparative analysis of passenger ride comfort in passive and active suspension systems. The bump road profile for generation of vibrations in vehicle system, running at the speed of 40 km/h is shown in Fig. 5. The selected parameters for quarter car system are as follows: m_P = 70 kg, m_s = 300 kg, m_u = 40 kg, c_P = 800 N/m/s, c_s = 1550 N/m/s, k_P = 8000 N/m, k_s = 25 000 N/m and k_t = 180 000 N/m respectively. The secondary suspension system of active quarter system is integrated with FLC and STFLC respectively. The passenger ride comfort is evaluated in terms of passenger seat acceleration and displacement responses.

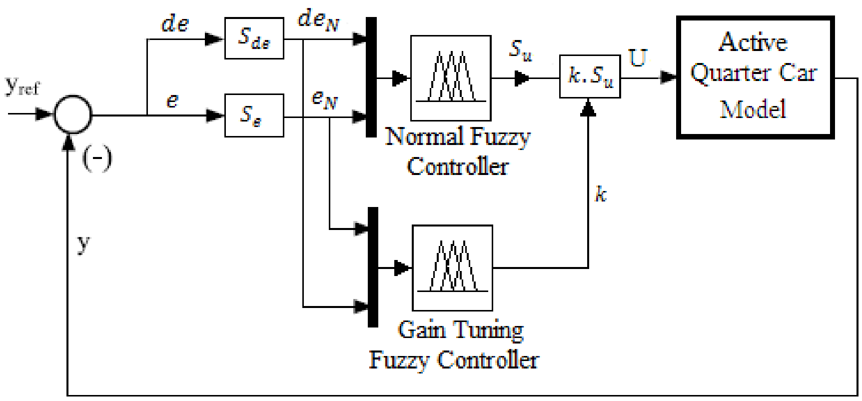

Fig. 3 Block diagram of self-tuning fuzzy controller

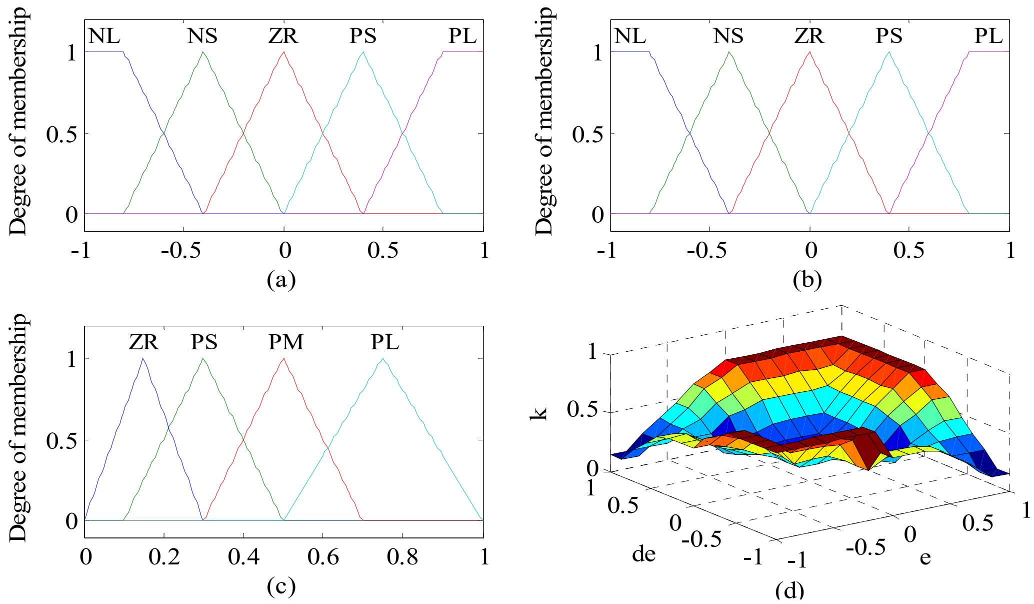

Fig. 4 MFs for STFLC (a) Input variable, e ; (b) Input variable, de; (c) Output variable, k ; (d) Surface plot

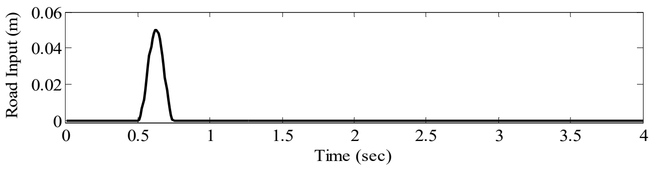

Fig. 5 Bump road profile

A. Time Domain Analysis

The simulation result of passenger seat acceleration and displacement is presented in Fig. 6. It can be seen from Fig. 6 that vehicle suspension system with FLC and STFLC controller achieved reduced passenger seat acceleration and displacement results. Furthermore, the best performance is provided by STFLC controlled suspension system in terms of passenger seat vibration control response. Figs. 7 and 8 display the control force supplied by controllers and power absorbed by controllers in suspension system under various control strategies.

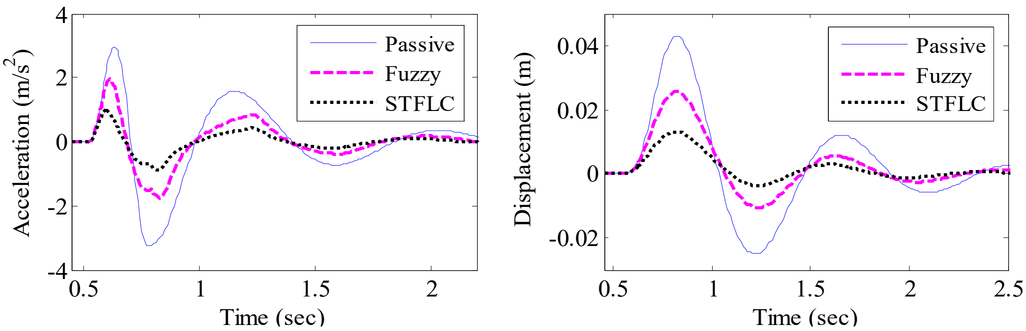

Fig. 6 Bump response (a) Passenger seat acceleration (b) Passenger seat displacement

Table III shows the mathematical response of passenger seat vibrations for peak and RMS (root mean square) values for uncontrolled as well as various fuzzy controlled active quarter car cases. It can be seen from mathematical results that all controlled cases provide improved response for passenger seat vibration control compared to uncontrolled case. But STFLC controlled suspension case provides best response in terms of passenger ride comfort issues.

TABLE III
PASSENGER SEAT RESULTS UNDER BUMP ROAD PROFILE

Controller Type	Acceleration (m/s^2)		Displacement (m)	
	Peak	RMS	Peak	RMS
Uncontrolled	2.965	0.897	0.043	0.011
FLC	1.941	0.500	0.026	0.006
STFLC	0.998	0.245	0.013	0.003

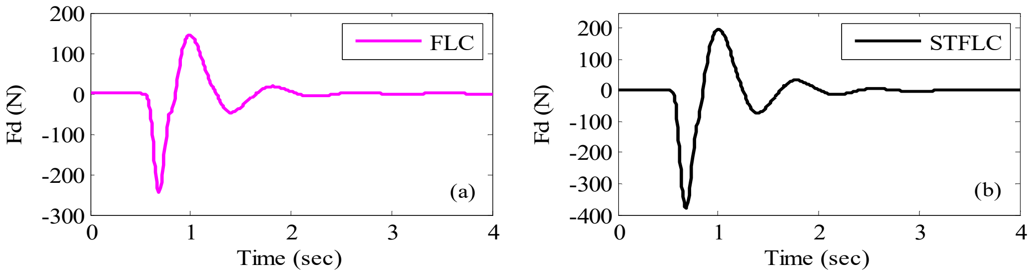

Fig. 7 Control force supplied by controllers (a) FLC (b) STFLC

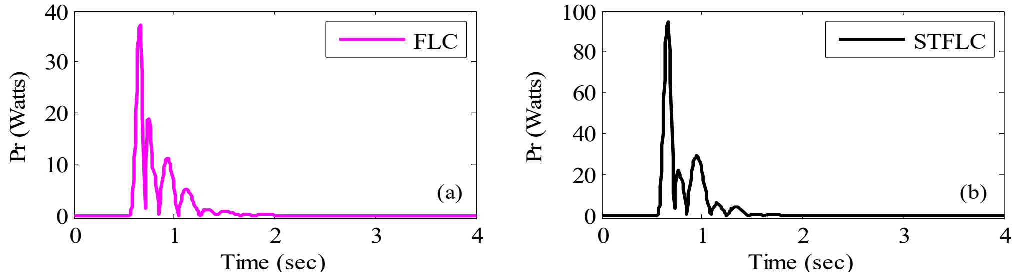

Fig. 8 Power absorbed by controllers (a) FLC (b) STFLC

TABLE IV
COMPARISON OF CONTROLLERS

Controllers	Performance			
	IAE	ITAE	ISE	ITSE
Uncontrolled	0.0275	6.70e-04	0.0325	1.85e-04
FLC	0.0161	3.29e-04	0.0164	3.12e-05
STFLC	0.0106	2.35e-04	0.0095	5.16e-06

Table IV represents four different criteria to evaluate the controller's performance related to integral of square error (ISE), integral of time multiplied absolute error (ITAE), integral of absolute error (IAE) and integral of time multiplied square error (ITSE) respectively. From the calculated mathematical data, it can be seen that all controlled cases provide improved results compared to uncontrolled one. In comparison with various controlled and uncontrolled cases, STFLC controlled suspension system achieved best performance on IAE, ITAE, ISE and ITSE criteria.

B. Frequency Domain Analysis

The frequency response of passenger seat acceleration and displacement for uncontrolled and controlled cases is shown in Fig. 9. The quarter car system has 3 degrees of freedom so there are 3 resonance values at 1.1402, 2.0294 and 11.4053 [Hz] respectively. Frequency response analysis was carried out to obtain the response at the resonance frequency values for the quarter car system. Both FLC and STFLC controlled cases show lower curves in Fig. 9 compared to uncontrolled one near the passenger seat resonance region. But the superior response in terms of magnitude at the passenger seat resonance values is shown by STFLC controlled case indicating the improved passenger ride comfort in quarter car model.

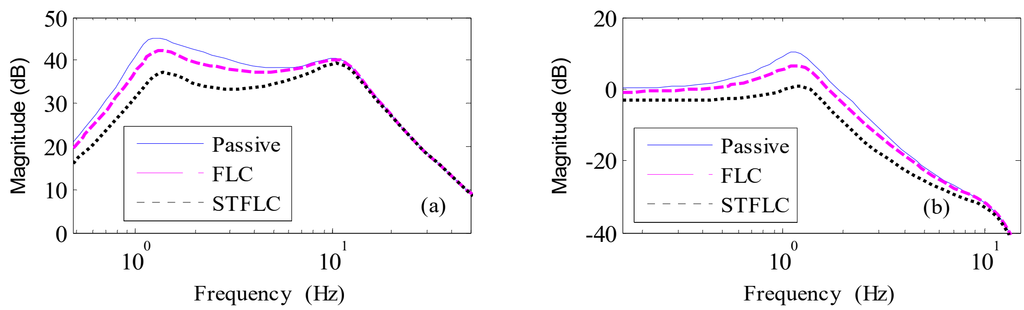

Fig. 9 Bode plot (a) Passenger seat acceleration (b) Passenger seat displacement

The frequency response for passenger seat acceleration and displacement transmissibility are shown in Fig. 10. The criterion selected for the same is shown in (4) and (5). It can be seen that the passenger seat acceleration and displacement transmissibility response are improved for both controlled cases. But the best response is shown by active vehicle with STFLC controller integrated suspension system.

$$Acceleration\ Transmissibility = \frac{Passenger\ seat\ acceleration\ response}{Road\ input} \quad (4)$$

$$Displacement\ Transmissibility = \frac{Passenger\ seat\ displacement\ response}{Road\ input} \quad (5)$$

The frequency response plot using power spectral density (PSD) of the passenger seat acceleration and displacement is shown in Fig. 11 for uncontrolled and active suspension cases.

From the obtained PSD results of passenger seat response, it can be seen that ride performance of travelling passenger in quarter car model is substantially improved for STFLC controlled case compared to other controlled and uncontrolled cases in the neighborhood of passenger seat resonance.

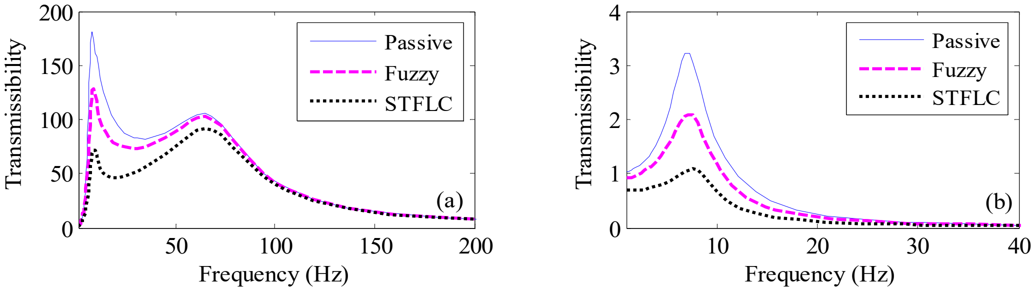

Fig. 10 Transmissibility (a) Passenger seat acceleration (b) Passenger seat displacement

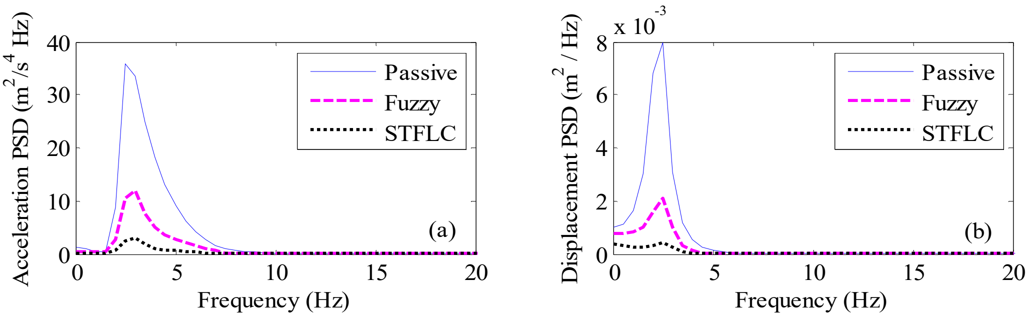

Fig. 11 (a) PSD of passenger seat acceleration (b) PSD of passenger seat displacement

V. Conclusions

In this research work, passenger seat response using quarter car model with three degrees of freedom was studied for ride comfort issues. For this purpose, FLC and STFLC were used in secondary suspension of quarter car model. The passenger seat acceleration and displacement responses of uncontrolled and controlled suspension systems were compared under bump road excitation. Simulation results demonstrated that STFLC controlled suspension system suppressed passenger seat acceleration and displacement response in best way and provided maximum ride comfort to travelling passenger compared to other cases. The IAE, ITAE, ISE and ITSE values of STFLC controlled active quarter car were minimum in simulation response compared to other two cases. The PSD response, frequency response and transmissibility response of passenger seat in terms of acceleration and displacement graphs also supported the effectiveness of STFLC controller. In conclusion, STFLC controller can be successfully used in secondary suspension of active quarter car system to achieve improved ride comfort experience of travelling passengers.

References

[1] Hassan, S.A., & Sharp, R.S. (1986). The relative performance capability of passive, active and semiactive car suspension systems, SAE technical paper series 864901.
[2] Devdutt, & Aggarwal, M.L. (2014). Fuzzy control of passenger ride performance using MR shock absorber suspension in quarter car model, International Journal of Dynamics and Control, Springerlink, DOI 10.1007/s40435- 014-0128-z.
[3] Sie, W.T., Lian, R.J., & Lin, B.F. (2006). Enhancing grey prediction fuzzy controller for active suspension systems, Veh. Syst. Dyn., 44(5), 407–430.
[4] Fialho, I., & Balas, G. J. (2002). Road adaptive active suspension design using linear parameter-varying gain-scheduling, IEEE Trans. Contr. Syst. Technology, 10(1), 43 -54.
[5] Huang, S. J., & Lin, W. C. (2003). A neural network sliding controller for active vehicle suspension," Materials Science Forum, 440-441, 119-126.
[6] Lauwerys, C., Swevers, J., & Sas, P. (2005). Robust linear control of an active suspension on a quarter car test-rig, Control Engineering Practice 13(5), 577-586.
[7] Huang, S. J., & Chen, H. Y. (2006). Adaptive sliding controller with self-tuning fuzzy compensation for vehicle suspension control, Mechatronics, 16, 607–22.
[8] Rajeswari, K.,& Lakshmi, P. (2008). GA tuned distance based fuzzy sliding mode controller for vehicle suspension systems, International Journal of Engineering and Technology, 5(1), 36- 47.
[9] Shirjoposht, N. P., Hassanzadeh, I., Hashemzadeh, F., & Alizadeh G. (2010). Optimal active suspension control based on a quarter-car model: an analytical solution, International Journal of Vehicle Safety (IJVS) 5(1), 1-20.
[10] Sun, W., Gao, H., & Kaynak, O. (2011). Finite frequency H∞ control for vehicle active suspension systems, IEEE Trans. Control Syst. Technol. 19, 416–22.
[11] Guon, L. X., & Zhang, L. P. (2012). Robust H∞ control of active vehicle suspension under non-stationary running, Journal of Sound and Vibration, 331, 5824–5837.
[12] Lian, R. J. (2013). Enhanced Adaptive Self-Organizing Fuzzy Sliding-Mode Controller for Active Suspension Systems, IEEE Transactions on Industrial Electronics, 60(3), 958-968.

[13] Deshpande, V. S., Mohan, B., Shendge, P. D., & Phadke, S. B. (2014). Disturbance observer based sliding mode control of active suspension systems, Journal of Sound and Vibration, 333, 2281–2296.
[14] Fard, H. M., & Samadi, F. (2015). Active Suspension System Control Using Adaptive Neuro Fuzzy (ANFIS) Controller, IJE Transactions C: Aspects, 28(3), 396-401.
[15] Devdutt, & Aggarwal, M.L. (2014). Fuzzy Logic Control of a Semi-Active Quarter Car System, International Journal of Mechanical, Industrial Science and Engineering, World Academy of Science, Engineering and Technology, 8(1), 163-167.
[16] Devdutt, & Aggarwal, M.L. (2015). Passenger seat vibration control of a semi-active quarter car system with hybrid Fuzzy – PID approach, International Journal of Dynamics and Control, Springerlink, DOI 10.1007/s 40435-015-0175-0.
[17] Kumar, M S. & Vijayarangan, S. (2006) Design of LQR controller for active suspension system," Indian Journal of Engineering & Materials Sciences, 13, 173-179.