

A tunable fuzzy logic controller for vehicle-active suspension systems

M.V.C. Rao* and V. Prahlad

Department of Electrical Engineering, Indian Institute of Technology, Madras 600036, India

Received February 1995; revised October 1995

Abstract

A novel fuzzy-logic-based control for vehicle-active suspension is suggested. The vehicle vibration and disturbance are reduced considerably with a fuzzy logic controller, to enhance comfort in riding faced with uncertain road terrains. A quarter-car active suspension system is controlled to reduce the vertical acceleration to a level of, that of, a hypothetical reference model. A new look-up table for the rule base of the fuzzy logic controller has been developed. The parameters, like, the spread, flex and centre of the bell-shaped membership functions associated with the different linguistic variables are fine tuned by trial and error method to get the suspension acceleration and deflection on par with that of the model. Simulation studies clearly demonstrate the effectiveness of the fuzzy logic controller for active suspension systems. The performance of the fuzzy logic controller under variations in the suspension component characteristics are also studied and was found to give reasonably good responses.

Keywords: Fuzzy logic controller; Linguistic variables; Vehicle-active and passive suspension systems; Quarter-car reference model

1. Introduction

Replacement of the spring damper suspensions of automobiles by (semi-)active systems has the potential of improving safety and comfort under nominal conditions [7]. A good vehicle suspension system has to reduce the sprung mass acceleration and provide adequate suspension deflection to maintain tire-terrain contact. This helps to improve ride comfort and vehicle maneuverability. Many methods have been developed in this regard, for

achieving quality ride control when faced with rough and unexpected road terrains. Betterment of the existing methods and the development of new alternative schemes are the major challenges faced currently by the automotive industries.

Active and semi-active suspension systems for vehicles have been suggested by many researchers. Venhovens [7] reported an adaptive semi-active suspension control based on the tyre load variations and an adjustable shock absorber within the vehicle suspension systems. Cheok [2] suggested an optimal model following suspension with micro-computerized damping. A discrete-time parametric linear quadratic control applied to active seat

* Corresponding author.

suspension control is seen in [1]. Sunwoo et al. [6] developed a model reference adaptive control (MRAC) for vehicle-active suspension systems with an ideal conceptual suspension model. They have used Lyapunov stability method in the design of the MRAC. Yeh and Tsao proposed a fuzzy preview control scheme of active suspension for rough roads [8], by sensing the road information ahead of the vehicle. A fuzzy logic control of vehicle suspension systems, can be seen in [4], where a model following fuzzy controller is suggested. They have used the error and change in error between the reference model acceleration and that of the active suspension as the two input variables in the fuzzy inference mechanism.

This work addresses the use of fuzzy-logic-based control for the vehicle-active suspension systems with the two variables going to the fuzzy controller as the active suspension velocity and deflection. Since the inception of fuzzy logic by Zadeh in 1965, it has been used in a variety of situations. The capability of fuzzy logic to model the real-world situations has resulted in its wider application in diverse fields as well. A fuzzy-logic-based control for vehicle-active suspension has been proposed and its capabilities for the improvement of ride comfort and vehicle manoeuvrability are studied through software simulation.

The passive and active suspension systems and a quarter-car model is briefly explained in Section 2. Section 3 deals with the fuzzy logic controller with the new look-up table for its rule base, for the active suspension systems. Simulation study and results can be found in Section 4, while the discussion is presented in Section 5.

2. Vehicle suspension systems and quarter-car model

Fig. 1(a) shows a conceptual sky-hook damping reference model. The desired suspension characteristics of this hypothetical ceiling mounted damper are characterized by the spring coefficient k_m (N/m), damping rate b_m (N/m/s) and the sprung mass m_m (kg). z_m (m) and w (m), respectively, give the sprung mass and wheel displacements. Thus,

$$m_m \ddot{z}_m = -k_m(z_m - w) - b_m \dot{z}_m \quad (1)$$

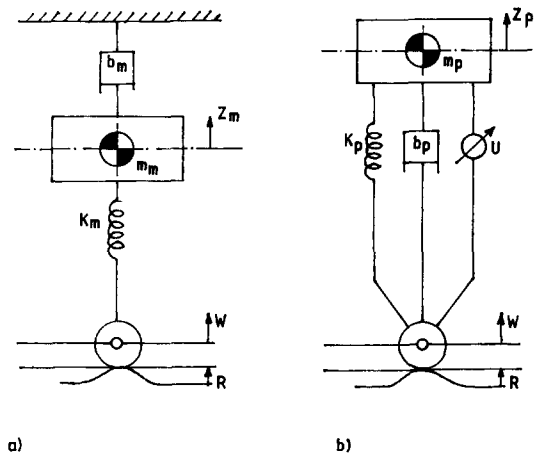


Fig. 1. (a) Sky-hook damping reference model. (b) Active suspension model.

gives the linear-dynamic equation for the reference model. Using adjustable shock absorbers in combination with an appropriate control strategy, ride comfort can be improved significantly over the passive suspension system [7]. An active suspension system is shown in Fig. 1(b). The dynamic equation for the sprung motion of this quarter-car active suspension system can be approximated by [6]

$$m_p \ddot{z}_p = -k_p(z_p - w) - b_p(\dot{z}_p - \dot{w}) + u, \quad (2)$$

where k_p and b_p are the coefficients of linearised spring and damping rates, m_p is the mass of the sprung load and u represents the applied actuator force for the active suspension. The deflections in the model suspension and the active suspension, can be arrived at, as

$$x_m = z_m - w, \quad (3)$$

$$x_p = z_p - w. \quad (4)$$

From Eqs. (1) and (3), the transfer functions from wheel displacement to sprung mass displacement and suspension deflection of the reference model can be obtained as

$$z_m(s) = \frac{k_m}{m_m s^2 + b_m s + k_m} w(s), \quad (5)$$

$$x_m(s) = \frac{-m_m s - b_m}{m_m s^2 + b_m s + k_m} \dot{w}(s). \quad (6)$$

The corresponding transfer functions for the active suspension systems with u set equal to zero, can be derived using Eqs. (2) and (4) as

$$z_{pw}(s) = \frac{b_p s + k_p}{m_p s^2 + b_p s + k_p} w(s), \tag{7}$$

$$x_{pw}(s) = \frac{-m_p s}{m_p s^2 + b_p s + k_p} \dot{w}(s), \tag{8}$$

and, with w set to zero as

$$z_{pu}(s) = \frac{1}{m_p s^2 + b_p s + k_p} u(s), \tag{9}$$

$$x_{pu}(s) = \frac{1}{m_p s^2 + b_p s + k_p} u(s). \tag{10}$$

From (7)–(10) the equations for sprung mass displacement z_p and suspension deflection x_p when both u and w are present, can be derived as

$$z_p(s) = \frac{b_p s + k_p}{m_p^2 s + b_p s + k_p} w(s) + \frac{1}{m_p^2 s + b_p s + k_p} u(s), \tag{11}$$

$$x_p(s) = \frac{-m_p s}{m_p^2 s + b_p s + k_p} \dot{w}(s) + \frac{1}{m_p^2 s + b_p s + k_p} u(s). \tag{12}$$

3. The fuzzy logic controller

Unlike boolean logic fuzzy logic deals with uncertain and imprecise situations. Linguistic variables

(SMALL, MEDIUM, LARGE, etc.) are used to represent the domain knowledge, with their membership values lying between 0 and 1. Basically, a fuzzy logic controller has got the following components [3].

(a) The fuzzification interface to scale and map the measured variables to suitable linguistic variables.

(b) A knowledge base comprising linguistic control rule base.

(c) A decision making logic to infer the fuzzy logic control action based on the measured variables, which is much akin to the human decision making.

(d) A defuzzification interface to scale and map the linguistic control actions inferred to yield a non-fuzzy control input to the plant being controlled.

The structure of the fuzzy logic control system for the vehicle active suspension is shown in Fig. 2. The suspension deflection x_p and the suspension velocity \dot{x}_p are the two input variables to the fuzzy logic controller while the change in control du is its output. Bell-shaped membership functions are used to represent the different linguistic variables for x_p , \dot{x}_p and du . These functions are realized by

$$\mu_{Li}(x, a_i, b_i, c_i) = \frac{1}{1 + [[(x - c_i)/a_i]^2]^{b_i}}, \tag{13}$$

with a_i deciding the spread and b_i deciding the flex of the two sides of the bell-shaped functions centred at c_i . The set $\{a_i, b_i, c_i\}$ constitutes the associated parameter set. These sets for the different linguistic variables Li , form the tunable parameters of the

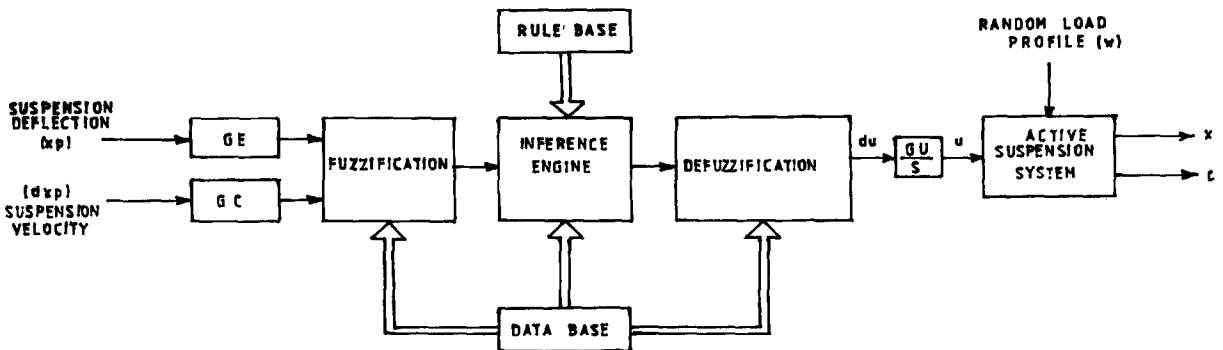


Fig. 2. Structure of the fuzzy controlled active suspension system.

controller. A trial and error approach has been resorted to, to achieve a good controller performance.

Scaling factors GE and GC are used for the suspension deflection and velocity to appropriately map them to the respective universes of discourses. A rule base developed by heuristics with suspension deflection and velocity as input variables, is given in Table 1. This table differs from the traditional Mac-Vicar Whelan look-up table for fuzzy logic controllers by having the linguistic variable zero for the controller output spread more about the centre of the table along its off diagonal. This stems from the fact that as the suspension velocity is close to zero the change in control action needed is zero.

The membership grade of the change in control action $du(k)$ at any instant k is determined by

$$\mu(du(k)) = F[\mu(GE xp(k)), \mu(GC dxp(k))], \quad (14)$$

Table 1
Rule base for fuzzy logic controller

		Suspension deflection						
		NL	NM	NS	Z	PS	PM	PL
Sprung mass velocity	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

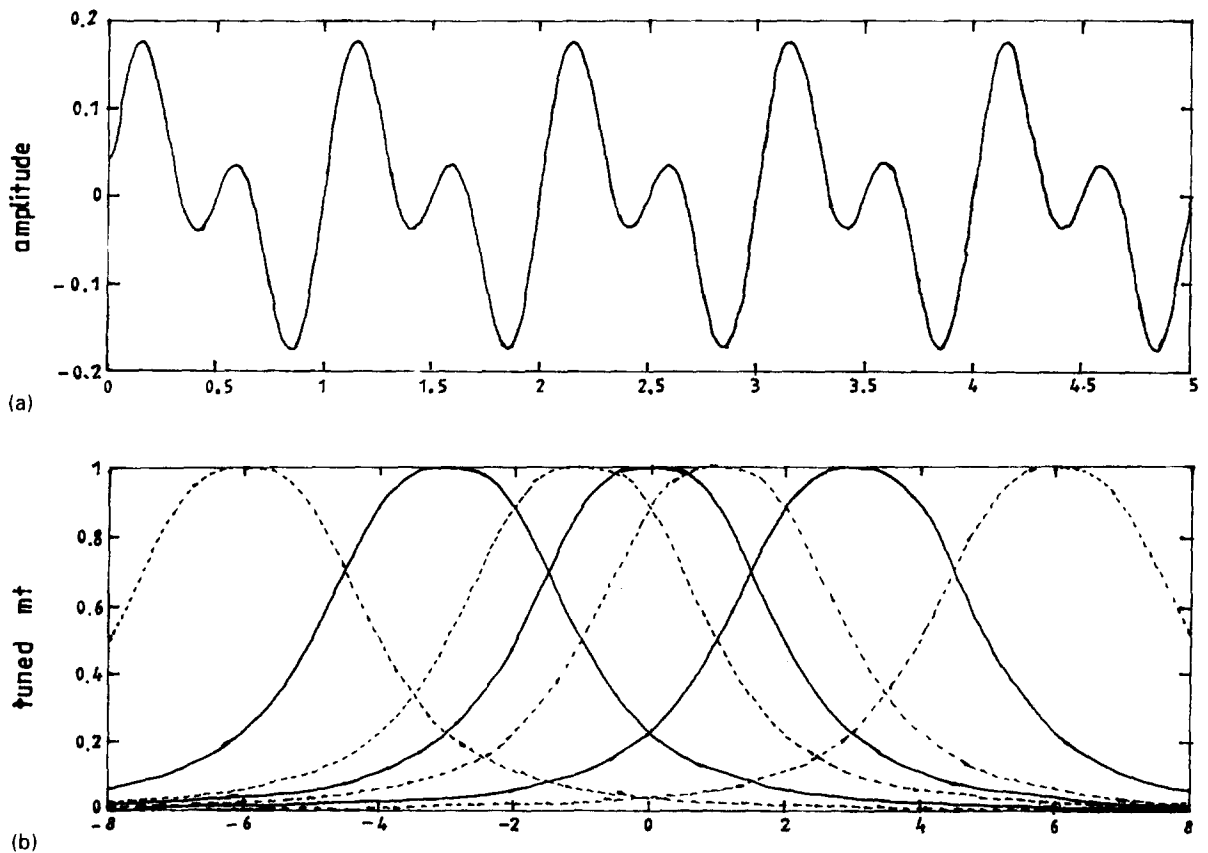


Fig. 3. (a) Time (sec) random road profile. (b) Suspension deflection.

where F denotes the fuzzy relation defined in the rule base. The conventional max-min composition rule of inference is used for arriving at the appropriate controller output.

The height method of defuzzification [5] is used for the change in control action du . Here the centroid of each output membership function for each rule is evaluated first and the final output is calculated as the average of the individual centroids, weighted by their heights (degree of memberships) as

$$du = \frac{\sum \mu_i(du)c_i}{\sum \mu_i(du)} \quad (15)$$

The final control signal acting on the suspension is

$$u(k) = GUdu(k), \quad (16)$$

Table 2
Parameters of MFs for suspension deflection

	{a, b, c}
NL	{2.0, 1.5, -6.0}
NM	{2.0, 1.5, -3.0}
NS	{2.0, 1.5, -1.0}
Z	{2.0, 1.5, 0.0}
PS	{2.0, 1.5, 1.0}
PM	{2.0, 1.5, 3.0}
PL	{2.0, 1.5, 6.0}

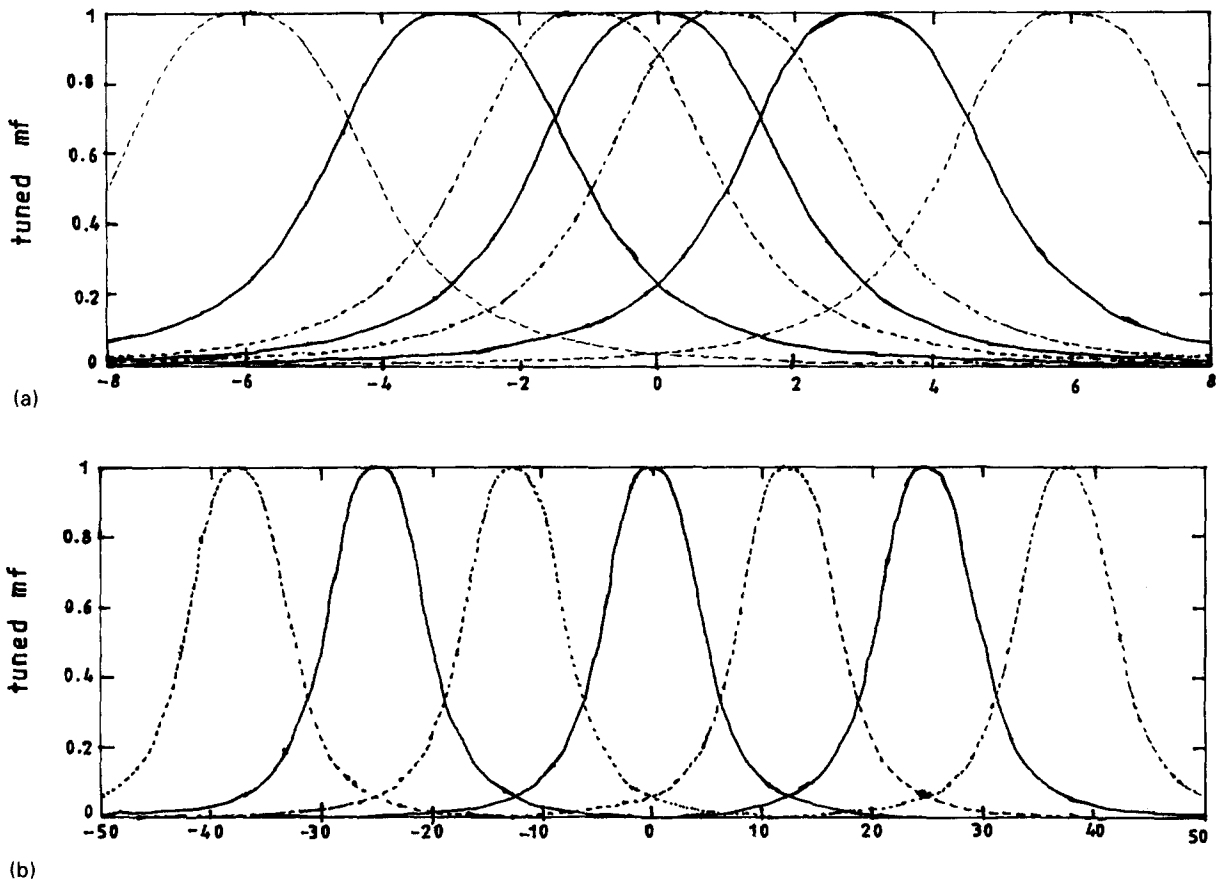


Fig. 4. (a) Suspension velocity. (b) Change in control.

Table 3
Parameters of MFs for suspension velocity

	{a, b, c}
NL	{5.0, 1.5, -6.0}
NM	{2.0, 1.5, -3.0}
NS	{2.0, 1.5, -1.0}
Z	{2.0, 1.5, 0.0}
PS	{2.0, 1.5, 1.0}
PM	{2.0, 1.5, 3.0}
PL	{5.0, 1.5, 6.0}

Table 4
Parameters of MFs for change in control action

	{a, b, c}
NL	{5.0, 1.5, -37.5}
NM	{5.0, 1.5, -25.0}
NS	{5.0, 1.5, -12.5}
Z	{5.0, 1.5, 0.0}
PS	{5.0, 1.5, 12.5}
PM	{5.0, 1.5, 25.0}
PL	{5.0, 1.5, 37.5}

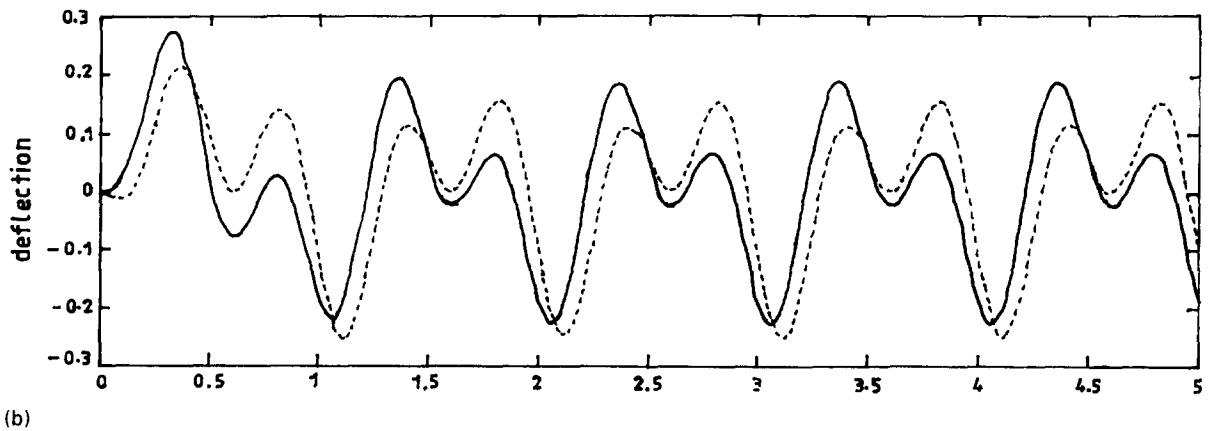
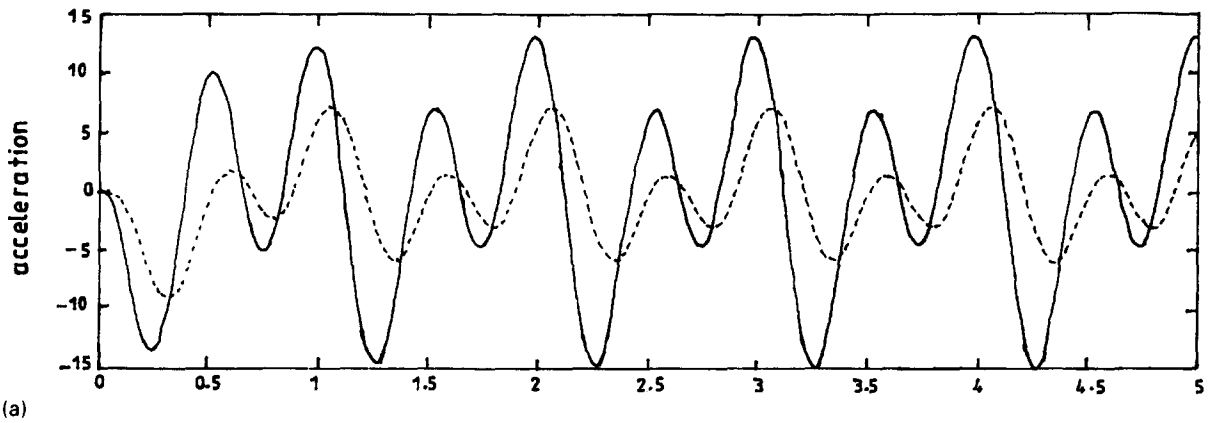


Fig. 5. (a) Time (sec). (--- model, — passive suspension). (b) Time (sec). (--- model, — passive suspension).

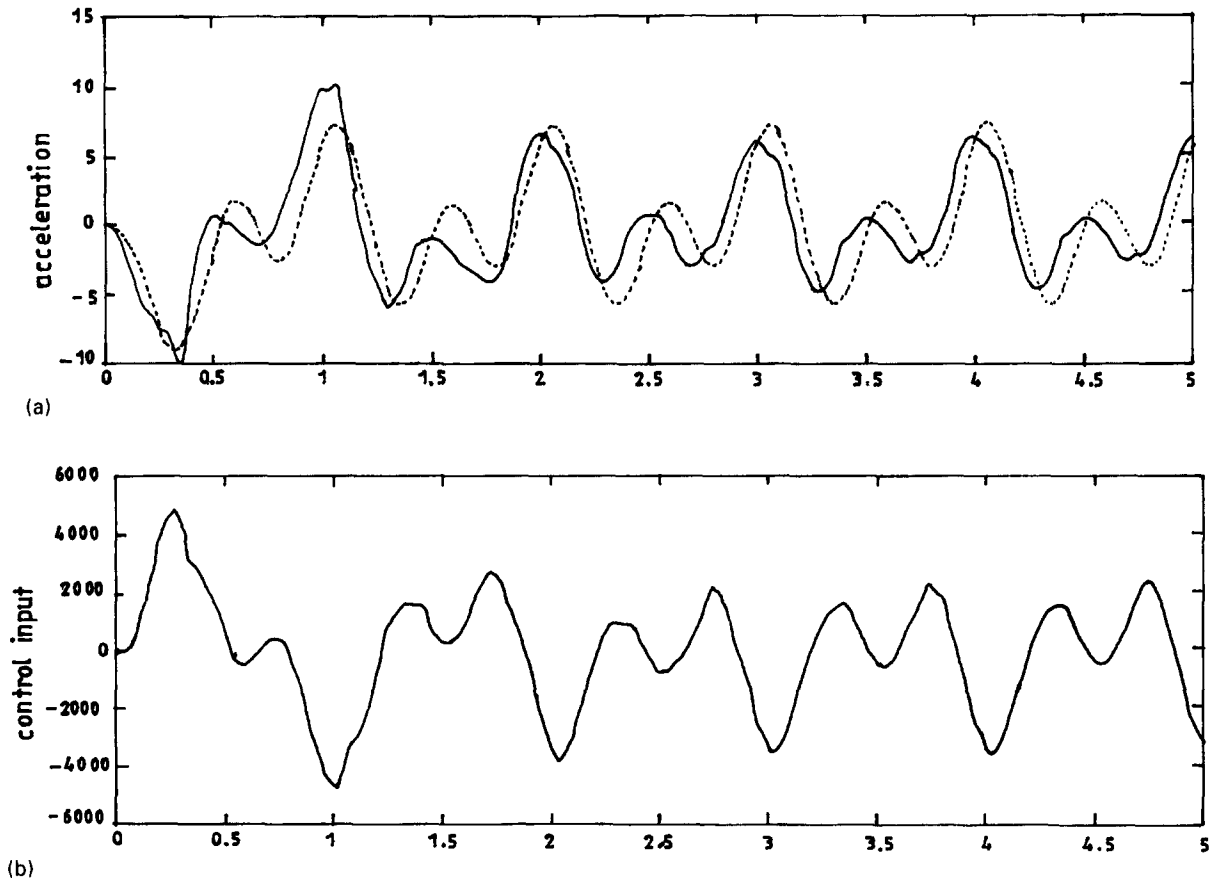


Fig. 6. (a) Time (sec). (--- model, — active suspension). (b) Time (sec).

with GU as the scaling factor for du . By looking at Eqs. (14) and (16), it can be inferred that this kind of fuzzy logic controller implementation falls in the family of proportional-derivative type.

4. Simulation study and results

For the quarter-car suspension systems given in Section 2, the typical parameters for the suspension model are selected as [6]: $m_m = 355$ kg, $k_m = 15000$ N/m and $b_m = 3000$ N/m/s. The corresponding parameters for the active suspension plant are chosen as $m_p = 355$ kg, $k_p = 14384$ N/m and $b_p = 1860$ N/m/s, typical of a commercial vehicle.

A sampling time of 0.01 s is selected for both the model and plant. The time domain response of the vehicle is simulated for a time period of 5 s over a pseudo-random road profile, with natural frequencies 1 and 2 Hz. The corresponding pseudo-random road profile is given in Fig. 3(a). The bell-shaped membership functions for the suspension deflection are plotted in Fig. 3(b). The respective tuned parameter sets for the different linguistic variables are given in Table 2.

The different universes of discourses for the suspension deflection, suspension velocity and change in control was taken as $[-8, 8]$, $[-8, 8]$ and $[-6000, 6000]$, respectively, for simulation purposes, resulting in the respective scaling factors GE,

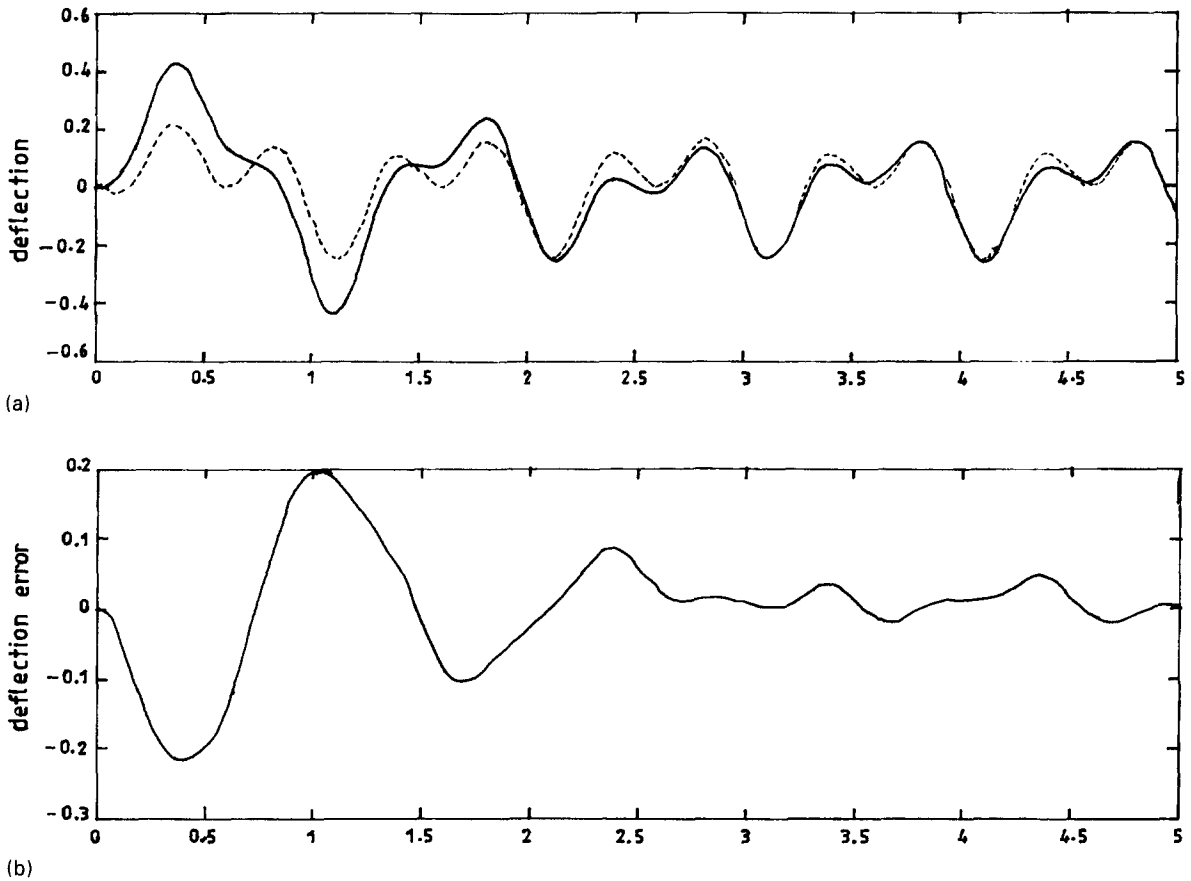


Fig. 7. (a) Time (sec). (--- model, — active suspension). (b) Time (sec).

GC and GU as 10, 1 and 300, respectively. Figs. 4(a) and (b), respectively, show the tuned bell-shaped membership functions for the suspension velocity and the change in control action. The associated parameter sets are given in Tables 3 and 4.

The suspension acceleration (m/s^2) for the model and the passive system are shown in Fig. 5(a), respectively, by dotted and continuous plots. The suspension deflection (m) for the same are depicted in Fig. 5(b). From these figures it can be observed that the suspension acceleration and deflection for the passive system are more than that of the reference model. The control action $u(0)$ is taken as 0 in this simulation study without any loss of generality. The suspension acceleration and control input (N) for the active system with the fuzzy logic controller in action are shown in Figs. 6(a) and (b). The

suspension deflection and the deflection error with respect to the reference model are available in Figs. 7(a) and (b). It can be seen from these figures that the suspension acceleration and deflection for the active system are brought to a level less than that of the reference model.

Figs. 8 and 9 give the similar results under a worst scenario, with 30% increment in sprung mass and a 30% decrement of both spring coefficient and damping rate from their nominal values. These plots clearly show the capability of the fuzzy active suspension to cope with wide variations in the parameters of the plant without retuning the controller's parameters. In Fig. 10 the responses of the system subjected to white noise between $t = 1$ s to $t = 3$ s is depicted along with the pseudo-random road profile.

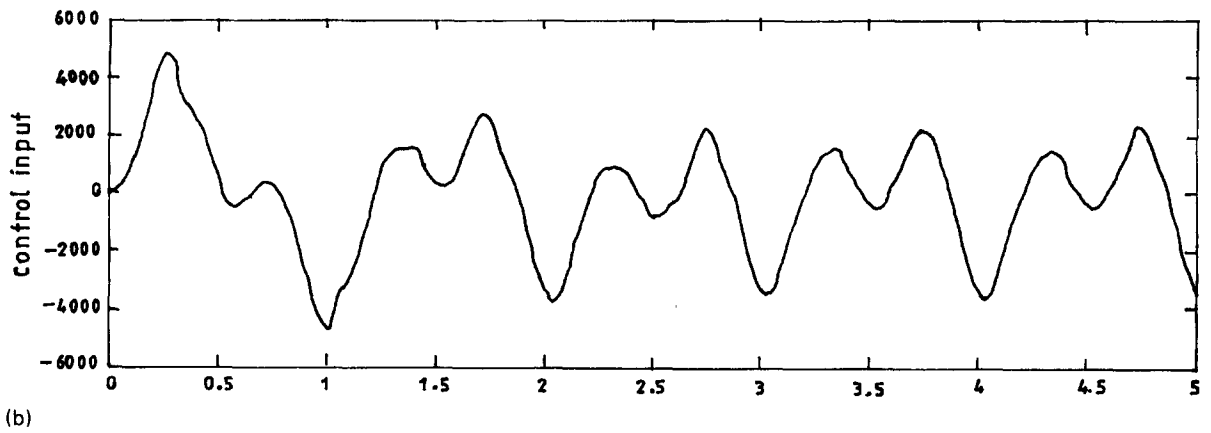
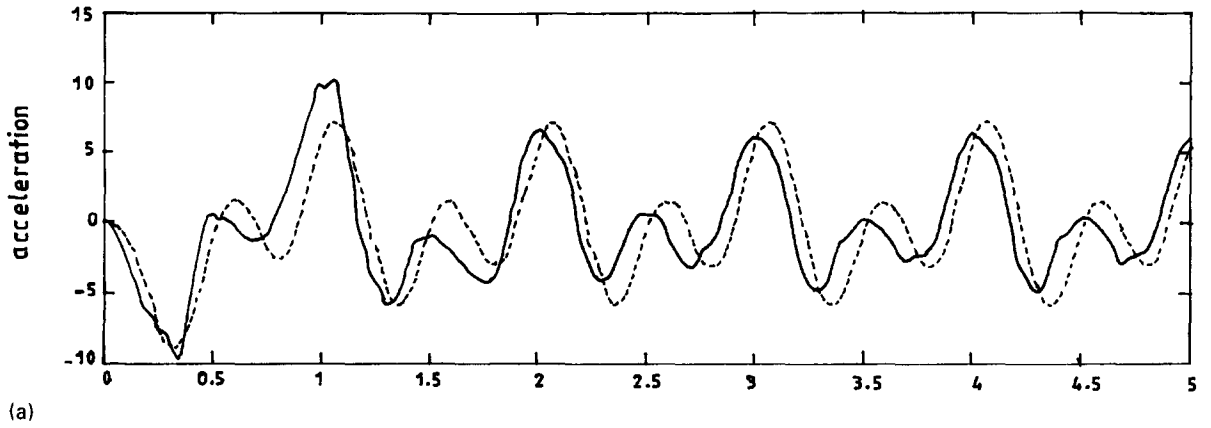


Fig. 8. (a) Time (sec). (--- model, — active suspension). (b) Time (sec).

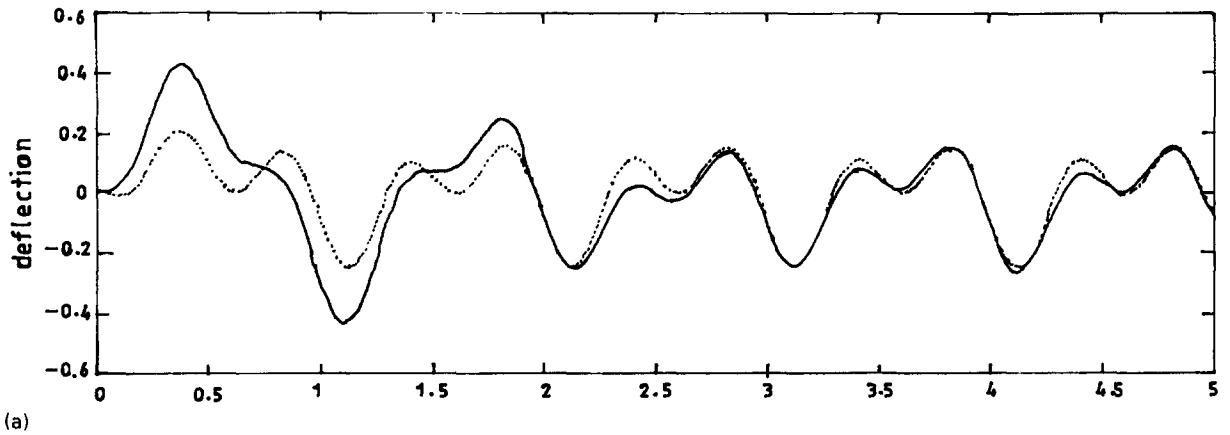


Fig. 9. (a) Time (sec). (--- model, — active suspension).

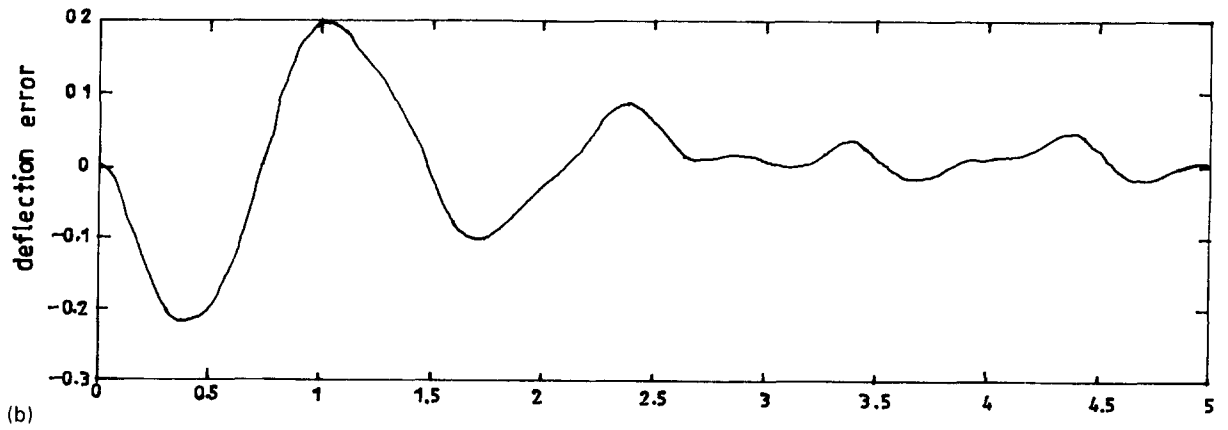


Fig. 9. (b) Time (sec).

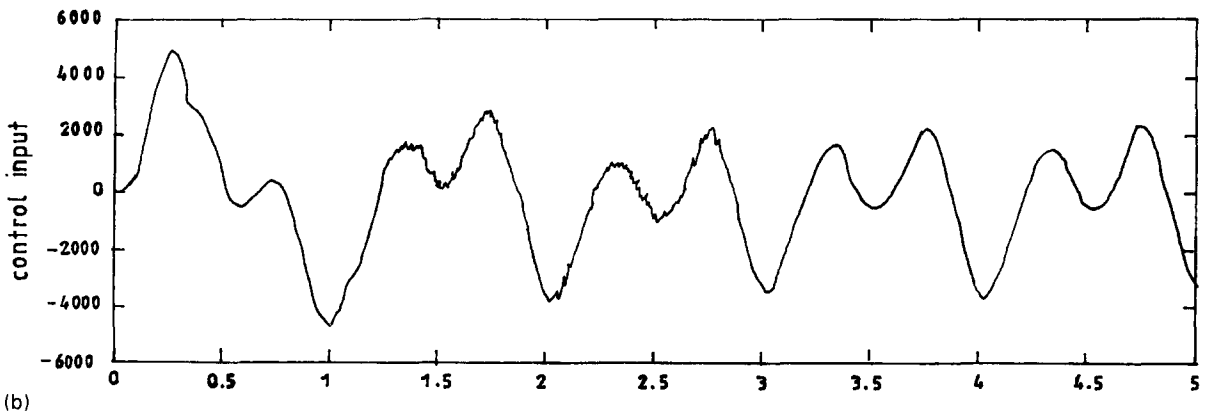
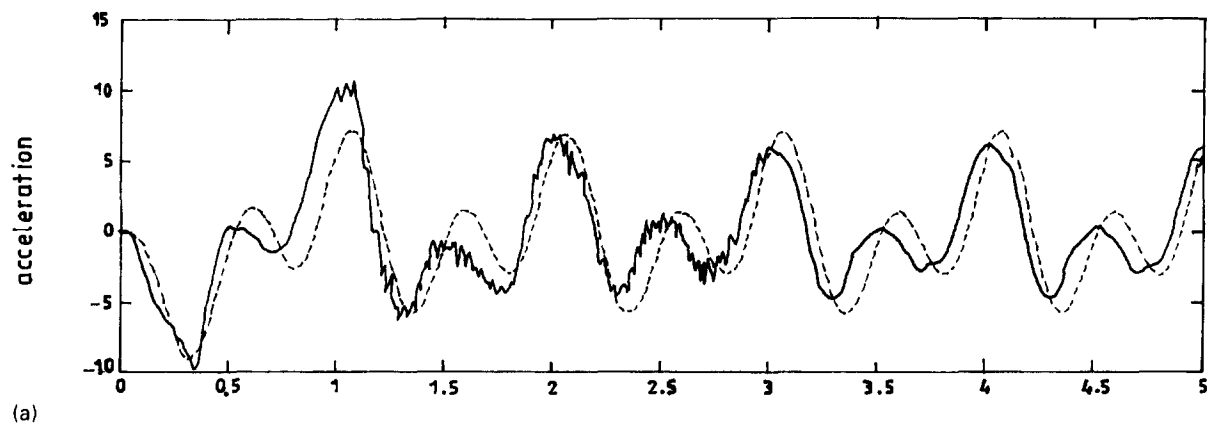


Fig. 10. (a) Time (sec). (— active suspension (solid), ——— model (dashed)). (b) Time (sec).

5. Discussion

A fuzzy-active suspension system for a quarter-car vehicle is presented. The proposed tunable fuzzy controller was found to bring down the suspension acceleration and deflection to a level to that of a hypothetical reference model. This results in better ride comfort. It was also observed that the controller is able to take care of the wider variations in the plant parameters from their nominal values. This study is mainly intended to demonstrate the application of fuzzy logic controllers in active suspension systems.

References

- [1] K.A.C. Cheok, H.X. Hu and N.K. Loh, Discrete-time frequency-shaping parametric LQ control with application to active seat suspension control, *IEEE Trans. Industrial Electron.* **36** (1989) 383–389.
- [2] K.A.C. Cheok, Nan-Khang Loh, H.D. Mcgee and T.F. Petit, Optimal model-following suspension with microcomputerized damping, *IEEE Trans. Industrial Electron.* **IE-32** (1985) 364–371.
- [3] C.C. Lee, Fuzzy logic control systems: fuzzy logic controller – Part 1, *IEEE Trans. System Man Cybernet.* **SMC-20** (1990) 404–418.
- [4] Y.-J. Lin, Y.-Q. Lu and J. Padovan, Fuzzy logic control of vehicle suspension systems, *Int. J. Vehicle Design* **14** (1993) 457–470.
- [5] G.C.D. Sousa and B.K. Bose, A fuzzy set theory based control of a phase-controlled converter DC machine drive, *IEEE Trans. Industrial Applications* **30** (1994) 34–44.
- [6] M.H. Sunwoo, K.C. Cheok and H.J. Huang, Model reference adaptive control for vehicle active suspension systems, IEEE Log. No. 9144904.
- [7] P.J.Th. Venhovens, The development and implementation of adaptive semi-active suspension control, *Vehicle System Dyn.* **23** (1994) 211–235.
- [8] E.C. Yeh and Y.J. Tsao, A fuzzy preview control scheme of active suspension for rough road, *Int. J. Vehicle Design* **15** (1994) 166–180.