Vibration Control of Active Vehicle Suspension System Using Fuzzy Logic Controller

A. Shehata, H. Metered and Walid A.H. Oraby

Abstract Fuzzy logic control (FLC) algorithm grants a means of converting a linguistic control technique and it is widely used in vehicle applications. This paper demonstrates the application of fuzzy logic technique to design a controller for the active vehicle suspension system to improve the suspension system performance by altering the number and arrangement of the rules set and the universe of discourses. A mathematical model and equations of motion of quarter vehicle active suspension is derived and solved using MATLAB/Simulink software. The proposed fuzzy controllers using 9, 25 and 49 rules set with two different types of membership functions, trapezoidal and triangle, are implemented in a closed loop control system to demonstrate the influence of the numbers of rule set and the type of membership function on the performance of suspension system. Suspension performance criteria were assessed in both time and frequency domains. Performance comparisons between the passive suspension, as a reference, and the proposed controllers of the active suspension were achieved. The simulation results indicate that the proposed active fuzzy controllers can dissipate the energy due to road excitation effectively and improves suspension performance. Among the investigated systems, the 25 rules set with a trapezoidal membership function for the fuzzy controller gives the best performance.

Keywords Active suspension system · Fuzzy logic control · Ride comfort · Vehicle stability · Vehicle suspension control

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1 Introduction

Through the design of a suspension system, a number of conflicting requirements has to be solved. The suspension system has to provide a comfortable ride and vertical vehicle stability at the same time. Also, enough contact between tires and road surface is needed in various driving conditions in order to maximize vehicle stability. Instead of a passive suspension, an active suspension can be applied in order to provide better resolve the trade-off between these conflicting requirements. Designing a good suspension system with optimum vibration performance under different road conditions is a significant undertaking.

Fuzzy logic is used to hold the active suspension and the membership functions are optimized by using genetic algorithm operations [1]. A fuzzy controller is designed with Interval type-2 FLC to improve the disturbance rejection of the suspension system which can be sourced by road shocks [2]. The vehicle vibration and disturbance are reduced considerably with a fuzzy logic controller, to improve comfort in riding faced with uncertain road terrains [3]. The ride comfort is improved by means of the diminution of the body acceleration when road disturbances from smooth road and real road roughness [4]. Fuzzy logic is used to control active suspension of a half-car model [5]. The fuzzy logic controller is based on two inputs, namely, suspension velocity and body velocity. The output of the fuzzy controller is the damping coefficient of the variable damper [6]. Fuzzy logic is used to tune each parameter of PID Controller and input membership function of fuzzy controller optimized by Discrete Action Reinforcement Learning Automata (DARLA) technique [7].

Active suspension system of a quarter car model using adaptive fuzzy logic and active force control strategies [8]. A fuzzy logic controller is designed for the control of the seven degrees of freedom full vehicle model [9]. An active control based on fuzzy logic is constructed such as a result as of the vehicle body acceleration, suspension working space and dynamic tire load. The amplitude of vertical vehicle both, from the view of ride comfort of passengers, is minimized under the restraint of the suspension travel, relative velocity, body velocity, wheel speed and tire deflection. The development of a better-quality suspension system remains an important increase objective for the automotive industry. A vehicle suspension system should have the qualifications to reduce the displacement and acceleration of the vehicle body, to achieve its advantages not only in the ride comfort aspect, but also minimizes the dynamic binding of the tire to maintain better tire–terrain contact. In this article, six fuzzy controllers are proposed for active suspension system. Intervals of fuzzy rules are designed in order to improve system robustness to noise measurement and external disturbances araised from road irregularities to the systems studied (passive and active) suspension systems. The remainder of this article is organized as follows; a quarter vehicle model is presented in Sect. 2. Section 3 introduces a brief description of the Fuzzy logic controller approach. Finally, the results are discussed in Sect. 4 and the extracted concliosions are in Sect. 5.

2 Quarter Vehicle Model

Figure 1 shows the two-degree-of-freedom system that represents the quarter vehicle model. It consists of an upper or body mass, m_b, as well as a lower or wheel mass, m_w.

By applying the Newton's second law, the body and wheel accelerations can be written as follows:

$$\ddot{Z}_b = \frac{f_d - k_s(Z_b - Z_w) - c_s(\dot{Z}_b - \dot{Z}_w)}{M_b} \tag{1}$$

$$\ddot{Z}_w = \frac{-f_d + k_s(Z_b - Z_w) + c_s(\dot{Z}_b - \dot{Z}_w) - k_t(Z_w - Z_r)}{Mw} \tag{2}$$

$$x = [x_1, x_2, x_3, x_4] = [z_b, z_w, \dot{Z}_b, \dot{Z}_w] \tag{3}$$

where

Z_b Car body displacement
$\dot{Z}_b$ Car body velocity
Z_w Car wheel displacement
$\dot{Z}_w$ Car wheel velocity
f_d Actuator force
Z_r Excitation due to road disturbance

As a result, in the state space equation, the state variables are described in the A, B, C and D matrices as represented in the Eqs. (4) and (5)

$$\dot{x}(t) = Ax(t) + Bf_d(t) + DZ_r(t) \tag{4}$$

$$\begin{bmatrix} \dot{x}1 \\ \dot{x}2 \\ \dot{x}3 \\ \dot{x}4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{ks}{mb} & \frac{ks}{mb} & -\frac{cs}{mb} & \frac{cs}{mb} \\ \frac{ks}{mw} & -\frac{ks+kt}{mw} & \frac{cs}{mw} & -\frac{cs}{mw} \end{bmatrix} \begin{bmatrix} xb \\ xw \\ \dot{x}b \\ \dot{x}w \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -\frac{1}{mb} \\ \frac{1}{mw} \end{bmatrix} f_d + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{kt}{mw} \end{bmatrix} z_r \tag{5}$$

Let the measurements available for feedback be $y(t) = C\,x$ the output vector is assumed to be

$$y(t) = \begin{bmatrix} -\frac{ks}{mb} & \frac{ks}{mb} & -\frac{cs}{mb} & \frac{cs}{mb} \\ 1 & -1 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \ddot{z}b \\ sws \\ DTL \end{bmatrix} \tag{6}$$

The system parameters of the quarter car model are obtained from ref. [10].

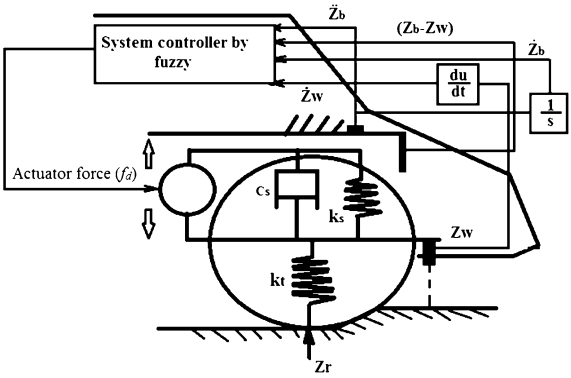


Fig. 1 Quarter-vehicle suspension model

3 Fuzzy Logic Controller Approach

This section offers a short description of the fuzzy controller that used to minimize the vibration levels to improve the suspension performance. Fuzzy rules are used to formulate the controller that can estimate expert reception and decision. The layout of the FLC is shown in Fig. 2.

The control rule Si, at any time i, is NB, ... , Z, ... , PB is represented by the linguistic descriptions (Mamdani), S1 = $(z_b - z_w)$, S2 = $(\dot{z}_b - \dot{z}_w)$, S3 = $\dot{z}_b$ and S4 = $\dot{z}_w$. There are four fuzzy inputs (S1, S2, S3, S4) and one output (f_d) with membership functions $\mu(z_b - z_w)$, $\mu(\dot{z}_b - \dot{z}_w)$, $\mu(\dot{z}_b)$ and $\mu(\dot{z}_w)$. FLC can be achieved by changing of universal of discourses and rule base through fuzzy to 9, 25 and 49 rules base. The fuzzy rule set is based on Table 1. Where, [NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), PB (positive big)], e is the error and ce is the change of error with respect to the time. Fuzzy Control used "Mamdani" method, the reasoning is the "min-max" method. Two common membership functions are used; triangular and trapezoidal. The two membership function are chosen for the input and output variables, as shown in Fig. 3.

For instance, the linguistic control rules of the fuzzy logic controller obtained from fuzzy control with 49 rules set used in such case are as follows:

$$\begin{aligned}
&\text{S1}: \text{ IF } \{\text{S1} = \text{ NB AND S2} = \text{NB AND S3} = \text{NB AND S4} = \text{NB }\} && \text{THEN } (f_d = \text{ NB})\\
&\text{S17}: \text{ IF } \{\text{S1} = \text{ NS AND S2} = \text{ NS AND S3} = \text{ NS AND S4} = \text{ NS }\} && \text{THEN } (f_d = \text{ NM})\\
&\text{S47}: \text{ IF } \{\text{S1} = \text{ PS OR PB AND S2} = \text{ PS OR PB AND S3} = \text{PS OR PB AND S4} = \text{ PS OR PB }\} && \text{THEN } (f_d = \text{ PB})\\
&\text{Si}: \text{ IF } \{(\text{S1, S2, S3, S4} = \text{Ei}) \text{ AND } ((\text{S1, S2, S3, S4} = \text{Gi})\} && \text{THEN } (f_d = \text{ Bi})
\end{aligned} \tag{6}$$

where Ei, Gi and Bi are labels of fuzzy sets representing the linguistic values S1 = $(z_b - z_w)$, $(\dot{z}_b - \dot{z}_w)$, S3 = $\dot{z}_b$, S4 = $\dot{z}_w$, e = error(S1), ce = change of error

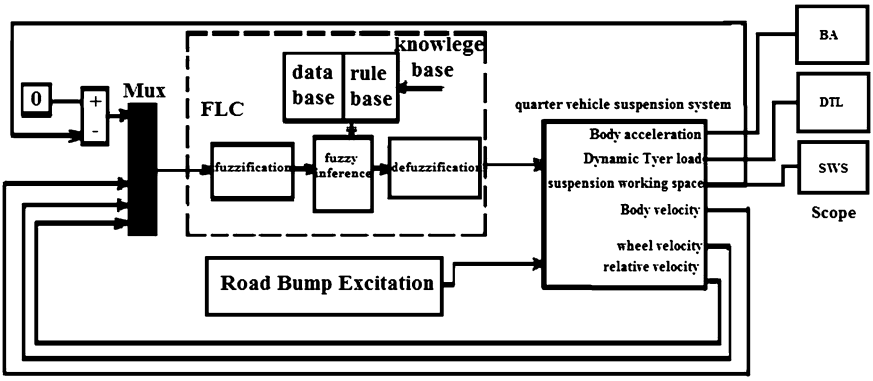


Fig. 2 Layout of the fuzzy logic control

Table 1 Fuzzy with 49 rules set

	e						
ce	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

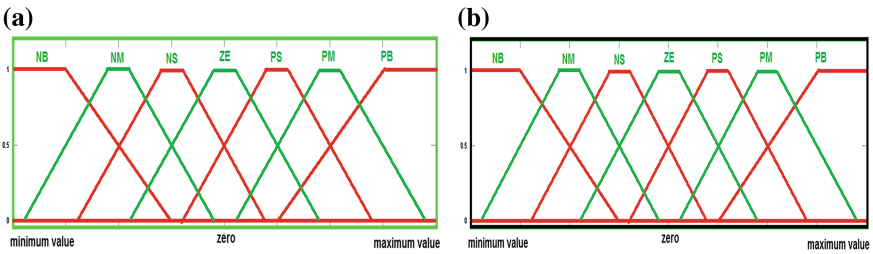


Fig. 3 Structure diagram for membership function trapmf type with 49 rules set. **a** e = S1, and ce = S2. **b** Actuator Force = f_d

(S2) and f_d = actuator force respectively, which are characterized by their membership functions. Also, the 9 and 25 rules set controller are formulated based on the same arrangement of the presented 49 rules shown in Fig. 3.

Defuzzification is the process for mapping from a set of secondary fuzzy control signals contained within a fuzzy output window to a non-fuzzy (crisp) control

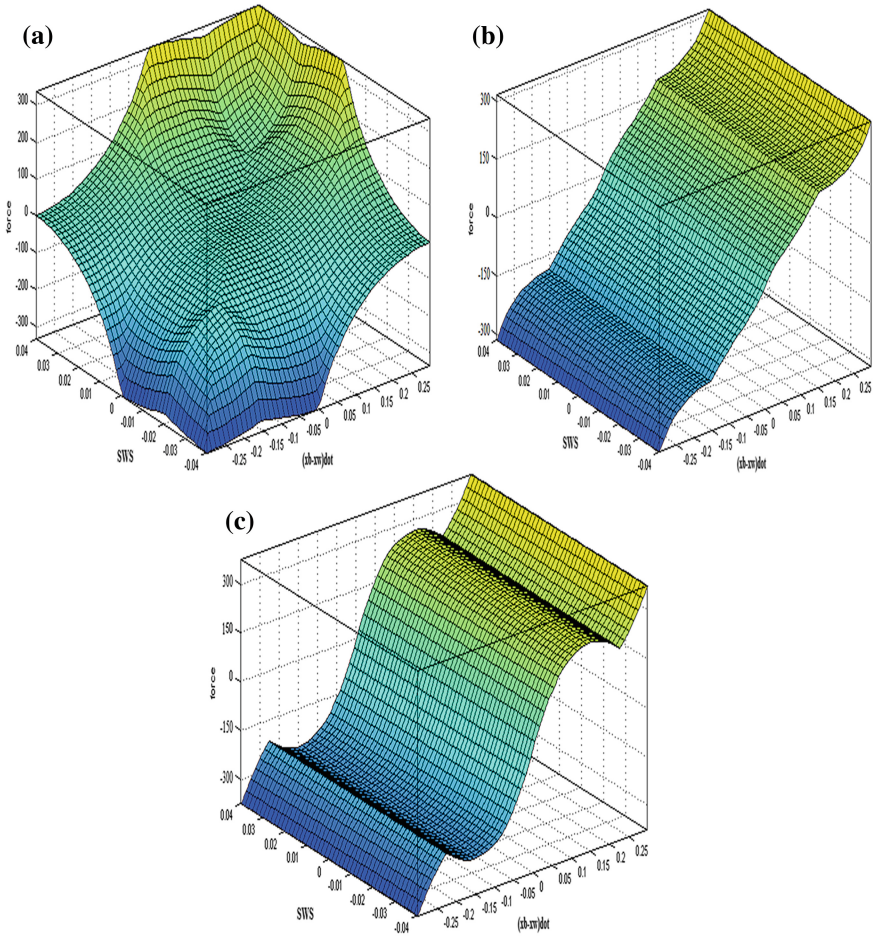


Fig. 4 Fuzzy surface with (9, 25 and 49) rules set, (**a**, **b** and **c**) respectively

signal. The center of region method is the most well identified defuzzification technique, which in linguistic conditions can be pronounced as:

$$f_d(\mathrm{t}) = \frac{\int f_d \times \mu(f_d)\mathrm{dt}}{\int \mu(f_d)\mathrm{dt}} \tag{7}$$

Figure 4 shows three fuzzy surfaces for the designed controllers using the trapezoidal membership function. The other surfaces using the triangle membership function are omitted.

4 Results and Discussion

The three main performance criteria in vehicle suspension design that manage the ride comfort and vehicle stability are suspension working space (SWS), vertical body acceleration (BA), and dynamic tire load (DTL). The BA is directly related to the ride comfort while tire's dynamic deformation ($Zw - Zr$) is required to achieve a good vehicle stability [11]. The suspension performance is improved when the SWS, BA, and DTL are minimized. There are four types of suspension systems investigated in this part:

(a) Conventional passive suspension system, with damping $c_s = 980$ Ns/m as in reference [12];
(b) Active suspension system, with 9 rules set fuzzy for both triangular and trapezoidal membership functions.
(c) Active suspension system, with 25 rules set fuzzy for both triangular and trapezoidal membership functions.
(d) Active suspension system, with 49 rules set fuzzy for both triangular and trapezoidal membership functions.

The above-mentioned performance criteria are used to calculate the performance of the control methods to select the best method of control to obtain the actuator force f_d for a given time history, as described in Sect. 3. Consequently, the damping of the conventional suspension system case is used as a reference for the comparisons with 3 active suspension systems proposed, noting that the value estimated for c_s is typical for automotive applications [12]. There are two types of road excitation, chosen to be very similar to the real-world road profiles, are considered in this study. First, time responses for the bumpy road input are being introduced. This style of road surface irregularity is one of the most encountered in actuality. Bump road input is formulated as presented in Eq. (8).

$$z_r = \begin{cases} a\{1 - \cos(\omega_r(t - 0.5))\}, & for\ 0.5 \le t \le 0.5 + \frac{d}{V} \\ 0, & otherwise \end{cases} \tag{8}$$

Where a is the half the bump amplitude, $\omega_r = 2\pi V/d$, d is the width of the bump, and V is the vehicle velocity. In this study the values for these parameters are, a = 0.035 m, d = 0.8 m, and V = 0.856 m/s [13]. The time history of the suspension system reaction under road bump excitation is shown in Fig. 5. The input of the fuzzy controller is composed of four input variables and one output variable. The relative displacement ($zb - zw$), relative velocity ($\dot{z}b - \dot{z}w$), body velocity $\dot{z}$b and wheel velocity $\dot{z}$w are defined as the input variables while the output variable is the controlling force based on the simulation software "Matlab/Simulink". The performance of the active control scheme is illustrated through a series of simulations. The time histories for SWS, BA, and DTL responses are shown in Fig. 5 and the Peak-To-Peak (PTP) values are shown in Fig. 6. The concluding figures show the comparison between the controlled active suspension system using

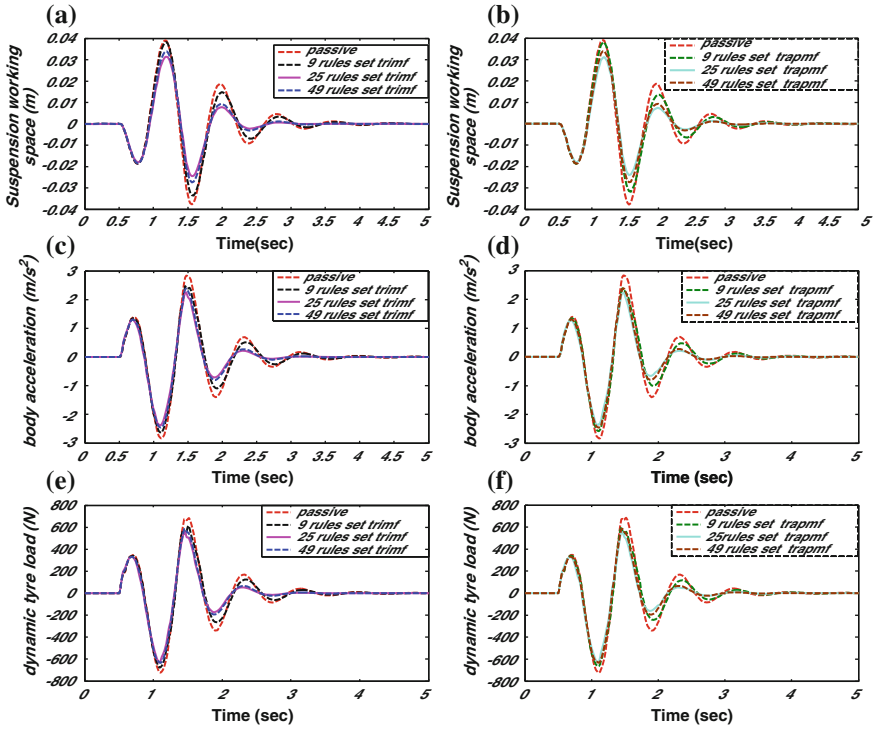
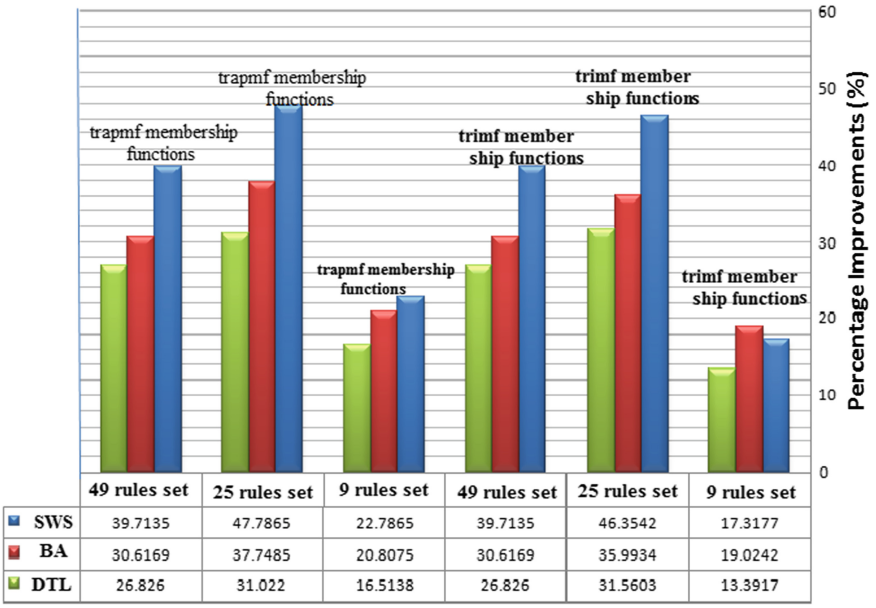


Fig. 5 The time domain of system responses under road bump excitation: **a**, **b** SWS; **c**, **d** BA; **e**, **f** DTL for both *trimf* and *trapmf* respectively

fuzzy with 9 rules set, fuzzy with 25 rules set and fuzzy with 49 rules set with both *trimf* and *trapmf*, and the conventional passive system. From these results it is seen that the fuzzy with 25 rules set controlled suspension can dissipate the energy due to bump excitation very well with both *trimf* and *trapmf*, reduce the settling time, and can improve not only ride comfort but also the vehicle stability.

The results indicate that, for the case of the fuzzy with 25 rules set control, the response is more continuous and the maximum value is lower than in the cases of fuzzy with 9 or 49 rules set controls for both *trimf* and *trapmf* and surely, better than the passive suspension system. The three controlled systems, both *trimf* and *trapmf* have the lowest peaks for the SWS, BA, and DTL, its values indicate an improved ride comfort and vehicle stability for the system response under road bump excitation. Figure 6 shows a complete comparison between all controllers for the peak-to-peak (PTP) values and their improvements percentages compared with passive suspension system. It's clearly shown that the 25 rules set with *trapmf* gives a superior performance. Moreover, the *trapmf* is counted as the best method of fuzzification and defuzzification process for SWS and BA while the *trimf* membership functions be in excess with DTL suspension performance.



	49 rules set	25 rules set	9 rules set	49 rules set	25 rules set	9 rules set
SWS	39.7135	47.7865	22.7865	39.7135	46.3542	17.3177
BA	30.6169	37.7485	20.8075	30.6169	35.9934	19.0242
DTL	26.826	31.022	16.5138	26.826	31.5603	13.3917

Fig. 6 Percentage improvements in PTP values for the controlled systems compared to passive system for road disturbance excitation

The second type of road excitation was a random road profile selected from ref. [12] and described mathematically as;

$$\dot{x}_r + \rho V x_r = V \mathrm{w_n} \tag{9}$$

where, w_n is white noise with the intensity $2\sigma^2\rho V$, ρ is the road irregularity parameter, and σ^2 is the covariance of road irregularity. In random road excitation, the values of road surface irregularity (ρ = 0. 45 m^{-1} and σ^2 = 300 mm^2) were selected assuming that the vehicle moves on the paved road with the constant speed V = 20 m/s, as in reference [13]. Isolate the vehicle body from the road disturbances also to reduce the resonance peak of the body mass proximity to 1 Hz; it is important to improve the ride comfort, which is a sensitive frequency of the human body. Furthermore, to improve vehicle stability, it is important to maintain the tire in contact with the road surface and therefore reduce the resonance peak proximity at 10 Hz, which is the resonance frequency of the wheel [14]. In view of these considerations, the results obtained from the excitation described by Eq. (9) are presented in the frequency domain. The modulus of the Fast Fourier Transform (FFT) of the SWS, BA and DTL over the range 0–16 Hz are shown in Fig. 7. The FFT was suitably scaled and smoothed by curve fitting as done in [12–15]. The lowest resonance peaks in the body and the wheel can be achieved using the projected 25 rules set fuzzy control strategy. These figures indicate that the

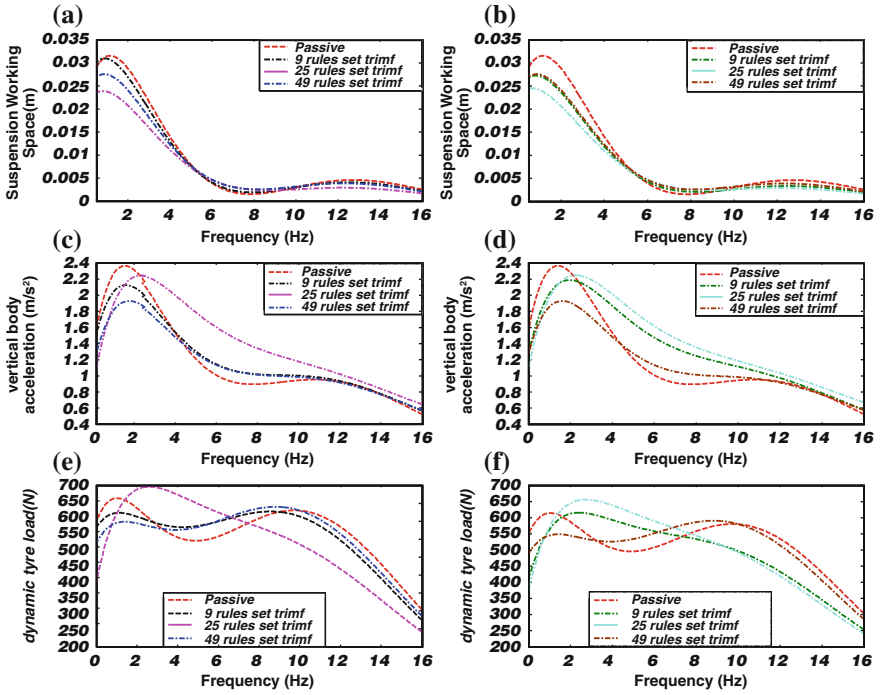


Fig. 7 The frequence domain responses under random road excitation: **a**, **b** SWS; **c**, **d** BA; **e**, **f** DTL for both *trimf* and *trapmf* respectively

technique of the fuzzy controlled system with 25 rules set, especially for *trimf*, dissipate the energy gained through the given road excitation in an excellent manner and thus, improves the SWS. On the other hand, the 49 rules set, for both *trimf* and *trapmf* achieves a significant improvement not only in terms of BA, which relates to the ride comfort, but also in DTL, which relates to the vehicle stability.

5 Conclusion

Control performance criteria were studied in the time domain and frequency domain to assessed the suspension effectiveness under bump and random road disturbance. The study implemented the 9, 25 and 49 rules set technique for the fuzzy controller of the active suspension system. From the time domain results, it had been concluded that these rules set can decrease the settling time and can improve ride comfort and vehicle stability over a conventional passive system. Comparing the number of rules set for the fuzzy controller for both *trimf, trapmf* implied that the 25 rules set improved SWS, BA and DTL over the 9 and even 49 rules set technique. Furthermore, frequency domain comparison between the three forms of fuzzy

controllers, clarifies that the 49 rules set technique with *trimf* or *trapmf* achieved a significant improvement in BA and DTL. Moreover, the 25 rules set technique overcomes the 49 technique in SWS over the frequency domain. This is in addition to the improved dynamic criteria in time domain.

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