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Logično mehko krmiljenje aktivnega vzmetenja brez upada njegove zračnosti

The Fuzzy-Logic Control of Active Suspensions without Suspension-Gap Degeneration

Rahmi Guclu

V tem prispevku uporabljamo model vozila s štirimi prostostnimi stopnjami z željo, da načrtamo in preverimo zmogljivosti aktivnega vzmetenja, ki ga logično mehko krmilimo, ne da bi kakorkoli zmanjšali delovno področje vzmetenja. Težnja k ničnemu premiku vzmetene mase utegne izničiti delovno razdaljo vzmetenja. Zato v tej raziskavi predlagamo nov pristop. Silostne izvršilnike vgradimo vzporedno z vzmetenjem. Osnovna zamisel, da predlagamo logično mehki krmilnik, izhaja iz dejstva, da je uspešen, iz možnosti, da takšen krmilnik uporabimo v vozilnih sistemih in iz možnosti, da s pomočjo logično mehkega algoritma premagamo upadanje zračnosti vzmetenja.Udobnost vožnje izboljšamo, tako da znižamo velikost gibov karoserije vozila. Poskakovanje karoserije in zibanje vozila modeliramo tako v časovnem (v primeru potovanja po nagnjeni stopničasti poti) kot v frekvenčnem prostoru. Rezultate simulacije primerjamo z rezultati pasivnega vzmetenja. Na koncu raziskave razpravljamo o zmogljivosti krmilnika s stališča udobnosti vožnje, o prednosti predlaganega pristopa in o izboljšanju zmogljivosti sistema.

(Ključne besede: modeli vozil, obese, logično mehki krmilniki, simuliranje)

In this paper a four-degrees-of-freedom vehicle model is used in order to design and check the performance of fuzzy-logic-controlled (FLC) active suspensions without causing any degeneration in the suspensions' working limits. Aiming at a zero displacement for a sprung mass might finish the suspensions' working distance. Therefore, in this paper a new approach is proposed. The force actuators are mounted parallel to the suspensions. The main idea behind proposing a fuzzy-logic controller is its success, the ability to use these types of controllers on vehicle systems and the ability to overcome the suspension-gap degeneration problem within the fuzzy-control algorithm. The improvement in the ride comfort is achieved by decreasing the amplitudes of the motions of the vehicle body. The body bounce and the pitch motions of the vehicle are simulated in both the time domain, in the case of travelling over a ramp-step road profile, and in the frequency domain. The simulation results are compared with the results from passive suspensions. At the end of the paper , the performance of the controller, the advantage of the proposed approach and the improvement in the system performance are discussed in terms of the ride comfort.

(Keywords: vehicle models, suspensions, fuzzy-logic controllers, simulations)

0 INTRODUCTION

The main functions of a vehicle's suspension system are to provide effective isolation from road-surface unevenness, to provide stability and directional control during handling maneuvers with ride comfort, and to provide support to the vehicle. Traditional vehicle-suspension systems are composed of two parallel components: the springs and the viscous dampers. Passive-suspension system designers are faced with the problem of determining the suspension's spring and damper coefficients. They have to compromise two important factors that conflict with each other: the ride comfort and the road holding. Good ride comfort needs soft springs; however, this means poor road holding. Furthermore, when talking about passive suspensions, there is no way to get rid of the resonance frequencies, such as the most important one at around 1 Hz, which is the result of the vehicle-body dynamics. Therefore, the improvement of vehicle-suspension systems has attracted more interest and been the subject of much research and development in recent years. This activity has two reasons: one is commercial and the other is scientific. The main reason for the commercial activity is the desire of automotive manufacturers to improve the performance and quality of their products. On the other hand, researchers and control-system designers have claimed that the automatic control of a vehicle-suspension system is possible when developments in actuators, sensors and electronics are considered. If the performance characteristic of a planned suspension system is taken into consideration, active suspension control becomes more attractive. In the past twenty years, many studies have been published on active and semi-active suspension systems. Most of the investigators used the quarter-car model. Procop and Sharp studied active automotive suspensions using road preview on a quarter model [1]. Hrovat surveys the applications of optimal control techniques to the design of active suspensions in one of his papers, starting with a quarter-vehicle model [2]. Non-linear control of a quarter-car active suspension is reviewed by Alleyne and Hedrick [3]. Burton and Truscott have brought together analyses of active and passive quarter-car systems and a full-scale test rig in their paper [4]. Redfield and Karnopp examined the optimal performance comparisons of variable-component suspensions on a quarter-car model [5]. Yu and Crolla presented an optimal self-tuning control algorithm using a quarter-car model, considering both external and internal disturbances [6]. Dan Cho presented the application of sliding-mode control to stabilize an electromagnetic suspension system with experimental results [7]. Yagiz *et al.* proposed the application of sliding-mode control on a quarter-vehicle model [8].

The aim of this paper is to apply fuzzy-logic control to automotive suspension systems without causing any degeneration of the suspension's working limits. If not prevented, as a result of the continuously changing elevation of the road surface, the classical approach of control algorithms has a negative effect on the suspension gap, preventing the suspensions and controllers from functioning and causing a very harsh ride.

Fuzzy logic has come a long way since it was first presented in 1965, when Zadeh published his seminal paper "Fuzzy Sets" in the Journal Information and Control [9]. Since that time, the subject has been the focus of much independent research. The attention currently being paid to fuzzy logic is most likely the result of popular consumer products that employ fuzzy logic and the availability of FLC processors [10]. The superior qualities of this method include its simplicity and its satisfactory performance. The fuzzy-logic method has been proposed for the active control of vehicle-suspension systems ([11] to [13]).

1 VEHICLE MODEL

The physical model of the vehicle is presented in Figure 1. The controllers are placed between the sprung and unsprung masses in parallel. The vehicle model has four degrees of freedom: these are body bounce z_M, body pitch θ, front-wheel hop z_{mf} and rear-wheel hop z_{mr}. In this model, M and J represent the body mass and inertia, k_{sf} and k_{sr} are the front and rear suspension-spring constants, c_f and c_r are the front and rear damper coefficients, u_f and u_r are the control force inputs to the front and the rear of the vehicle, respectively. m_f and m_r are the front and rear unsprung masses, k_{tf} and k_{tr} are the stiffness of the front and rear wheels, $z_f(t)$ and $z_r(t)$ are the front- and rear-wheel inputs, respectively. The mathematical model of the vehicle is:

$$[M]\underline{\ddot{X}}+[C]\underline{\dot{X}}+[K]\underline{X}=[A]\underline{Z}+[B]\underline{U} \qquad (1),$$

where,

$$\underline{X}=\begin{bmatrix} z_M \\ \theta \\ z_{mf} \\ z_{mr} \end{bmatrix} \qquad (2).$$

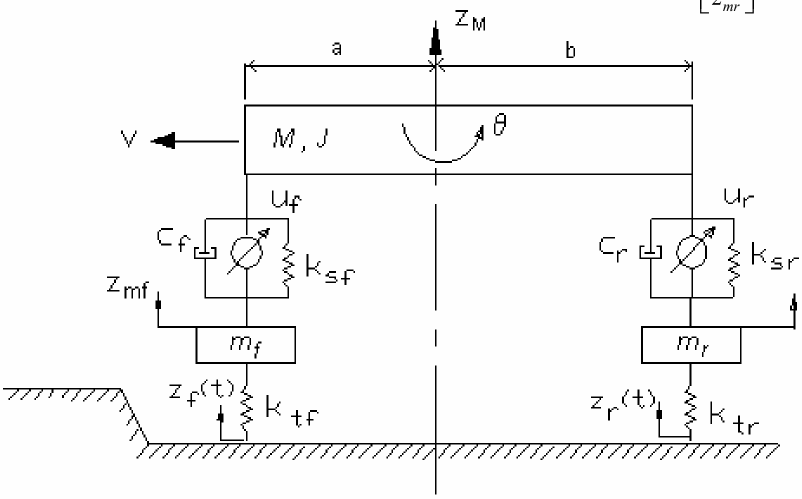

Fig. 1. *Vehicle model*

The mass matrix,

$$[M] = \begin{bmatrix} M & 0 & 0 & 0 \\ 0 & J & 0 & 0 \\ 0 & 0 & m_f & 0 \\ 0 & 0 & 0 & m_r \end{bmatrix} \qquad (3).$$

The damping matrix,

$$[C] = \begin{bmatrix} c_f + c_r & b.c_r - a.c_f & -c_f & -c_r \\ b.c_r - a.c_f & b^2.c_r - a^2.c_f & a.c_f & -b.c_r \\ -c_f & a.c_f & c_f & 0 \\ -c_r & -b.c_r & 0 & c_r \end{bmatrix} \qquad (4).$$

The stiffness matrix,

$$[K] = \begin{bmatrix} k_{sf} + k_{sr} & b.k_{sr} - a.k_{sf} & -k_{sf} & -k_{sr} \\ b.k_{sr} - a.k_{sf} & b^2.k_{sr} - a^2.k_{sf} & a.k_{sf} & -b.k_{sr} \\ -k_{sf} & a.k_{sf} & k_{sf} + k_{tf} & 0 \\ -k_{sr} & -b.k_{sr} & 0 & k_{tr} + k_{sr} \end{bmatrix} \qquad (5).$$

The road-surface inputs and related matrix,

$$\underline{Z} = \begin{bmatrix} z_f(t) \\ z_r(t) \end{bmatrix} \qquad [A] = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ k_{tf} & 0 \\ 0 & k_{tr} \end{bmatrix} \qquad (6).$$

It is obvious that there will be a time delay of δt between the front- and rear-wheel road inputs.

$$\delta t = (a+b)/V \qquad (7)$$

then,

$$z_r(t) = z_f(t - \delta t) \qquad (8).$$

The control inputs and the related matrix are

$$\underline{U} = \begin{bmatrix} u_f \\ u_r \end{bmatrix} \qquad [B] = \begin{bmatrix} 1 & 1 \\ -a & b \\ -1 & 0 \\ 0 & -1 \end{bmatrix} \qquad (9).$$

2 THE FUZZY-LOGIC CONTROLLER DESIGN

Linguistic variables, such as Small, Medium, and Big are used to represent the domain knowledge, with their membership values lying between 0 and 1. Basically, a fuzzy-logic controller has the following components:

(i) The fuzzification interface to scale and map the measured variables to suitable linguistic variables (fuzzyfier).
(ii) A knowledge base comprising a linguistic control rule base.
(iii) A decision-making logic to infer the fuzzy-logic control action based on the measured variables, which resembles human decision-making (the fuzzy-reasoning engine).
(iv) A defuzzification interface to scale and map the linguistic control actions inferred to yield a non-fuzzy control input to the plant being controlled (defuzzyfier).

The fuzzyfier converts each input variable value into the relevant fuzzy variable value using its own set of linguistic variables (fuzzy sets) and their pertinent membership functions. For example, for a generic input variable y_i the fuzzy sets Negative Very Big, Negative Big, Negative Small, Zero, Positive Small, Positive Big and Positive Very Big (nvb, nb, ns, ze, ps, pb and pvb) are defined in the universe of discourse of y_i. Any values of y_i in its universe of discourse belong at the same time to different fuzzy sets with a different degree of membership, by the related membership functions (the most commonly used kind of membership functions are bell-shaped, trapezoidal and triangular). The fuzzy-reasoning engine converts the values of the fuzzy-input variables into the fuzzy sets of output variables. It consists of a set of the fuzzy-logic rules of the kind IF {rule premise} THEN {rule consequence}. The {rule premise} block is a set of fuzzy-logic operations, whose result, different from a set of Boolean logic operations, is any real value between 0 and 1. The basic operators of fuzzy logic are fuzzy intersection (AND), fuzzy union or disjunction (OR) and fuzzy complement (NOT); their operands are fuzzy sets. The result of the AND (OR) operation is the minimum (maximum) of the membership functions of its two fuzzy-set operands; the result of the NOT operation is the complement of the membership function of its fuzzy-set operand. The {rule consequence} provides a linguistic value for each output variable; its truth value is the numeric result (between 0 and 1) of the {rule premise}. Fuzzy sets and their pertinent membership functions have to be defined for each output. The defuzzyfier is responsible for the translation of the fuzzy-reasoning engine results into a crisp set of output values. A variety of methods are used to perform defuzzyfication, the most common being:

i) The Mamdani method, which returns the centroid of the output fuzzy region as the crisp output of the fuzzy interface system.
ii) The TVFI (Truth Value Flow Inference) method, which returns a weighted average as the crisp output of the fuzzy interface system [14].

In the conventional control approach, the aim is to follow the zero displacement as a reference value for the body-bounce motion. But when this is realized, it is found that the suspension working limits degenerate as much as the amplitude of the road-surface displacement in order to compensate for the new difference in the elevation of the vehicle body. This causes the suspensions not to function after a certain time, causing them to become out of order. In order to overcome this practical difficulty, a new FLC approach is proposed. The algorithm of the MIMO

Table 1. *Rule base for the fuzzy-logic controllers*

$e(\dot{Z}_M - \dot{Z}_{Gaxis})$ $e(\dot{\theta} - \dot{\theta}_{Gaxis})$	$e(\dot{Z}_M)$ $e(\dot{\theta})$	$e(\ddot{Z}_M)$ $e(\ddot{\theta})$	u_z u_θ	$e(\dot{Z}_M - \dot{Z}_{Gaxis})$ $e(\dot{\theta} - \dot{\theta}_{Gaxis})$	$e(\dot{Z}_M)$ $e(\dot{\theta})$	$e(\ddot{Z}_M)$ $e(\ddot{\theta})$	u_z u_θ
PM	PM	ZE	ZE	PM	PM	P or N	PS
PS	PM	ZE	PS	PS	PM	P or N	PM
ZE	PM	ZE	PM	ZE	PM	P or N	PB
NS	PM	ZE	PM	NS	PM	P or N	PB
NM	PM	ZE	PB	NM	PM	P or N	PVB
PM	PS	ZE	ZE	PM	PS	P or N	PS
PS	PS	ZE	PS	PS	PS	P or N	PM
ZE	PS	ZE	PS	ZE	PS	P or N	PM
NS	PS	ZE	PM	NS	PS	P or N	PB
NM	PS	ZE	PM	NM	PS	P or N	PB
PM	ZE	ZE	NS	PM	ZE	P or N	NM
PS	ZE	ZE	ZE	PS	ZE	P or N	NS
ZE	ZE	ZE	ZE	ZE	ZE	P or N	ZE
NS	ZE	ZE	ZE	NS	ZE	P or N	PS
NM	ZE	ZE	PS	NM	ZE	P or N	PM
PM	NS	ZE	NM	PM	NS	P or N	NB
PS	NS	ZE	NM	PS	NS	P or N	NB
ZE	NS	ZE	NS	ZE	NS	P or N	NM
NS	NS	ZE	NS	NS	NS	P or N	NM
NM	NS	ZE	ZE	NM	NS	P or N	NS
PM	NM	ZE	NB	PM	NM	P or N	NVB
PS	NM	ZE	NM	PS	NM	P or N	NB
ZE	NM	ZE	NM	ZE	NM	P or N	NB
NS	NM	ZE	NS	NS	NM	P or N	NM
NM	NM	ZE	ZE	NM	NM	P or N	NS

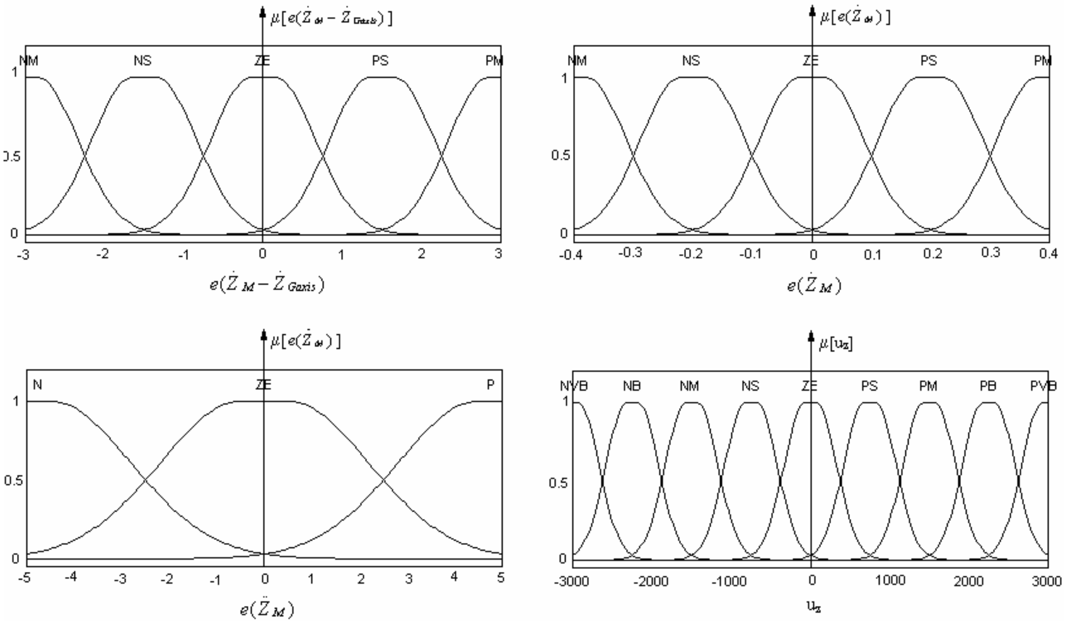

Fig. 2. *Membership-function plots of body bounce*

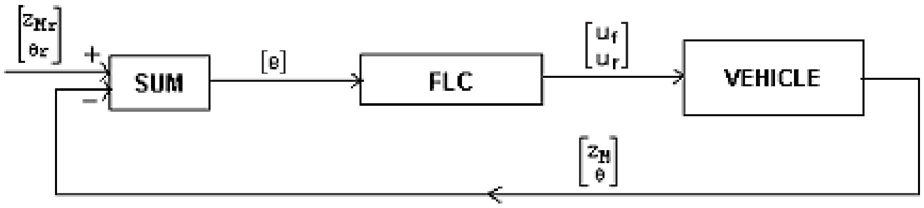

Fig. 3. *Closed-loop model of the vehicle with a fuzzy-logic controller*

fuzzy-logic controller for the vehicle-suspension system uses the errors of the vehicle-body motion velocity, and its acceleration and suspension-gap velocity as the input variables, while the control forces u_f and u_r are the outputs. A model of the two similar rule bases developed by analogy with errors for the body bounce and the pitch is given in Table 1. P, N, ZE, VB, B, M and S represent Positive, Negative, Zero, Very Big, Big, Medium and Small, respectively.

Control forces u_f and u_r are obtained after a decision about u_z and u_θ by FLC using the relations below:

$$u_f = (-u_\theta + bu_z)/(a+b) \quad (10)$$

$$u_r = (u_\theta + au_z)/(a+b) \quad (11).$$

The Gaussian membership functions used for the control of the body bounce are shown in Figure 2. Similar functions have also been used for pitch control.

3 SIMULATION

The closed-loop model of the fuzzy-logic controller for a vehicle-suspension system is presented in Figure 3. By defining the mathematical model of the system, the simulation is realized. The road disturbance is chosen as shown in Figure 4. It must be noted that there are two road inputs to the system: to the front wheel and, with a time delay δt, to the rear wheel.

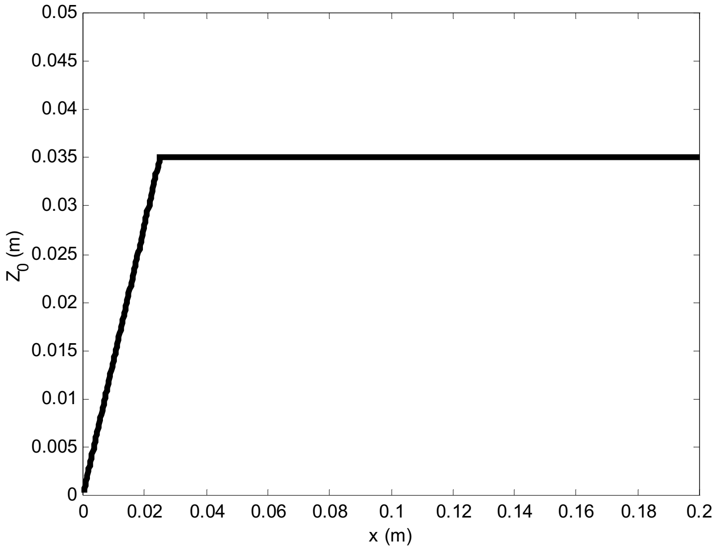

Fig. 4. *The road surface input*

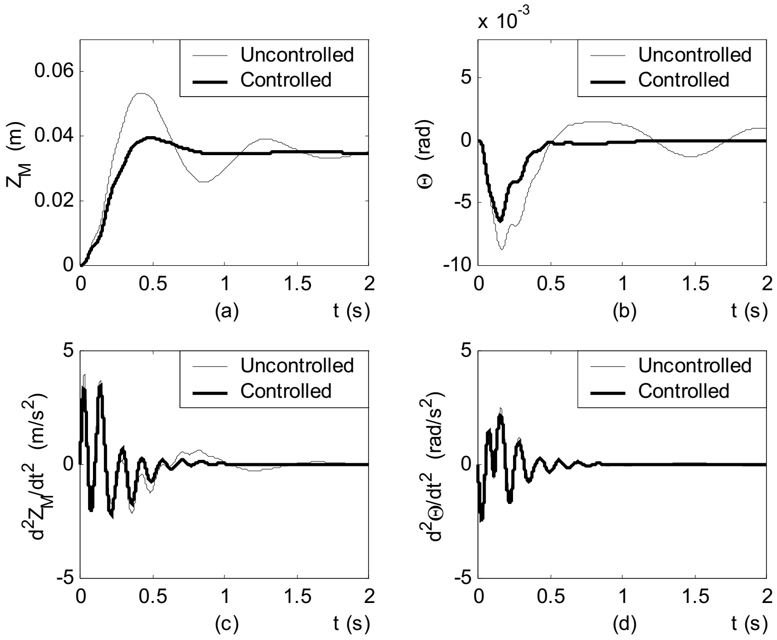

Fig. 5. *Time-response plots of the vehicle-body motions: (a) Vehicle-body displacement, (b) Pitch motion, c) Vehicle-body acceleration, (d) Pitch acceleration*

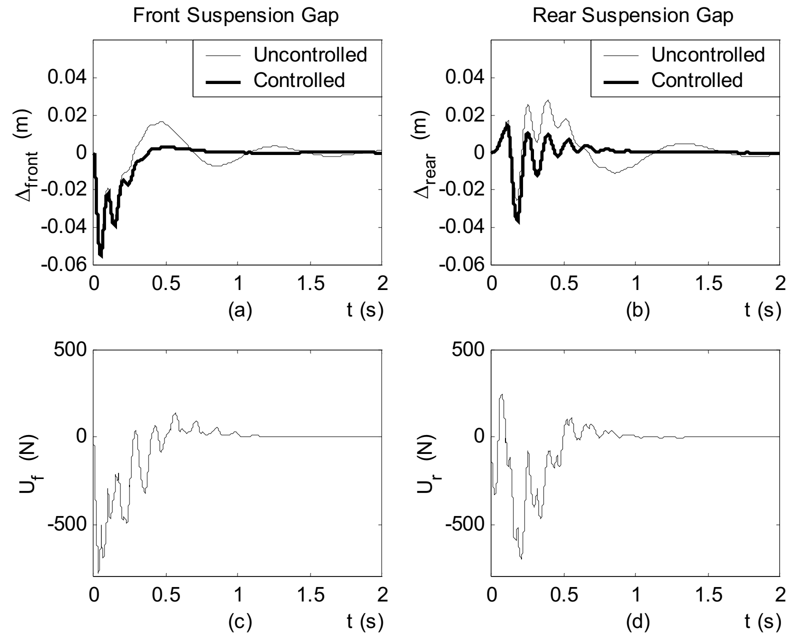

Fig. 6. *The system response of the vehicle and control force inputs: (a) Change in front suspension length, (b) Change in rear suspension length, (c) Front suspension control force, (d) Rear suspension control force*

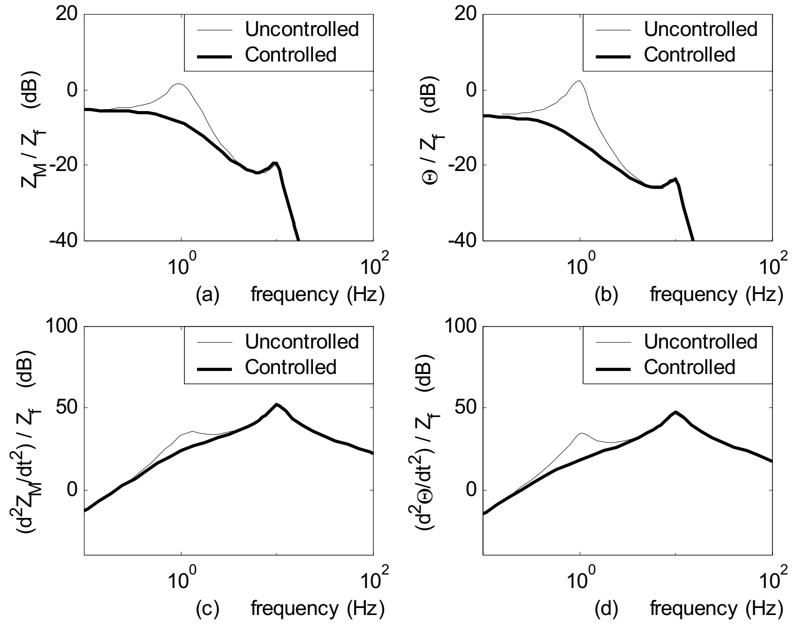

Fig. 7. *Frequency-response plots of the vehicle-body motions: (a) Vehicle-body displacement, (b) Pitch motion, (c) Vehicle-body acceleration, (d) Pitch acceleration*

The controlled and uncontrolled vehicle-body and pitch displacements and their accelerations are shown in Figure 5. The controlled vehicle-body and pitch motions reach the zero reference value much faster than the uncontrolled ones. The vehicle body mass follows a smooth trajectory against the road disturbances, coming from the front and rear wheels as seen in Figure 5.a. Since the final value of vehicle-body displacement is equal to the road-surface height there will be no loss in suspension working space.

In Figures 6.a and 6.b, the change in suspension length is simulated. As demonstrated in these figures, there is no permanent change in the suspension lengths. The maximum values of the control forces are around 800 N, as seen in Figures 6.c and 6.d.

When the frequency response of the system without controllers is checked, two resonance frequencies are observed around 1.1 and 10 Hz of the body motions and wheel hops in Figures 7.a and 7.b. On the other hand, when the controllers are active, the resonances of the body motions disappear and the amplitude of the motion over most of the frequency range gets smaller, as presented in the same figure. In Figures 7.c and 7.d, similar conclusions can be obtained if the frequency response of the accelerations of the body bounce and the pitch motion are checked. The improvement observed is very important when the ride comfort is taken into consideration.

4 CONCLUSION

In this paper, a fuzzy-logic controller for a vehicle is designed and the simulation results are presented. The proposed control approach does not cause any degeneration in the suspension's working limits. The main idea behind proposing this controller is its success and the ability to use these types of controllers on vehicles with developing technology. The results of this paper prove that the performance of an active suspension of this type is superior to one of the passive ones, and the proposed approach solves the suspension-degeneration problem. The improvement in resonance values and the decrease in the vibration amplitudes in the frequency-response plots also proves that this type of controller with the proposed fuzzy-logic control approach improves the ride comfort significantly.

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