Strojniški vestnik - Journal of Mechanical Engineering 53(2007)4, 233-240
UDK - UDC 629.1.015:[681.5:004.8]
Kratki znanstveni prispevek - Short scientific paper (1.03)

Uporaba logično mehkega krmiljenja za izboljšanje udobja vožnje vozil

The Use of Fuzzy-Logic Control to Improve the Ride Comfort of Vehicles

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V prispevku smo predstavili povsem novo metodo mehke logike krmiljenja aktivnega obešenja vozila. S to metodo izboljšamo udobje potnikov v vozilu brez izgube delovnega prostora pri ustavljanju. Kot vstopne veličine smo izbrali odvod navpičnega pomika vozila, upogib obešenja in sestavo teh veličin, kot izstopno veličino pa silo izvršilnika. S tako izbiro vstopnih veličin zmanjšamo zalogo pravil in skrajšamo čas, potreben za izračun. Predlagano krmiljenje smo uporabili na četrtinskem modelu vozila, pri ugotavljanju časovne odvisnosti smo, da bi bolje raziskali delovanje krmilja, upoštevali različne vozne razmere. Na koncu smo predstavili še frekvenčni odziv ter uspešnost predlaganega krmilja.

(Ključne besede: mehka logika, krmiljenje aktivnega obešenja, vplivi na udobje, delovni prostor)

In this study, a brand new fuzzy-logic method for the active suspension control of a vehicle is introduced. The method improves the ride comfort of passengers without losing any of the working space of the suspension. The derivative of the vehicle's vertical body displacement, the suspension deflection, and the combination of these variables were chosen as the inputs, and the actuator force was the output of the controller. This choice of input combination leads to a reduced rule base and a shorter computation time. The proposed controller is applied to a quarter-car model, and for the time responses different road conditions are considered in order to give a better understanding of the performance of the controller. Finally, the frequency responses are presented and the success of the proposed controller is discussed.

(Keywords: fuzzy logic, active suspension control, ride comfort, suspension working space)

0 INTRODUCTION

The main functions of vehicle suspensions are to suppress the vibration of the vehicle body and to achieve tire-road contact. Reducing the acceleration and displacement of the vehicle body provides the ride comfort for the passengers. Generally, vehicle suspensions are classified as passive, semi-active and active systems [1]. The term passive describes a suspension that is made up of the traditional suspension elements, i.e., a spring and damper. In passive suspensions the control objectives are obtained for limited frequencies and there is a conflict between the ride comfort, the road holding and the suspension deflection ([1] to [4]). Therefore, semi-active and active systems are receiving a great deal of interest in investigations to overcome these problems. Variable dampers or magneto-rheological (MR) dampers are used in semi-active suspension systems, whereas active suspensions include various actuators, like pneumatic, hydraulic, etc. In most of the studies these elements are used in parallel with passive elements to achieve the desired performance ([1], [2], [5] and [6]). In active suspension systems, controllers use the suspension working space by changing the original suspension length. Thus, in the controller design stage the suspension deflection should be taken into account; if not, the control action could cause the controllers to lock themselves and not to function properly, which leads to a harsh ride.

Different control methods are used in semi-active and active suspension systems. Fuzzy-logic control is one of the innovative control methods; it is based on the fuzzy-logic theory presented by Zadeh [7]. It is preferred because of its applicability to systems where the mathematical model is not known exactly and its ability to express the knowledge of experts in linguistic form ([8] and [9]). Much research has involved suspension control with fuzzy logic. Lee [10] presented a detailed survey of the fuzzy-logic controller in which a general methodology for constructing a fuzzy-logic controller and assessing its performance is described. D'Amato and Viassolo [11] proposed a controller including fuzzy logic to minimize vertical car-body acceleration and to avoid hitting the suspension's limits. Al-Holou *et al.* [12] combined the sliding-mode, fuzzy-logic, and neural-network control methodologies in order to enhance the ride and comfort. Huang and Lin [13] proposed an adaptive fuzzy sliding-mode controller to suppress the sprung-mass position oscillation due to road-surface variations. Guclu [14] presented a fuzzy-logic control for a vehicle without causing any degradation in the suspension's working limits. Kou and Li [15] proposed a GA-based Fuzzy PI/PD controller for a quarter-car active suspension system where the suspension deflection and its derivative are used as the inputs. Caponetto *et al.* [16] proposed a fuzzy-control approach to a sky-hook semi-active suspension system, where the fuzzy controller is optimized by means of a genetic algorithm. Sharkawy [17] proposed an adaptive fuzzy controller for a quarter-car active suspension system where the adaptive law is obtained using Lyapunov's direct method. An improvement in ride comfort and road handling with respect to LQR was shown via simulations. Rao and Prahlad [18] proposed a fuzzy-logic controller for a quarter-car model in which the inputs are the suspension deflection and its change, and the output is the change of the control signal. Yeh and Tsao [19] proposed a fuzzy-preview control scheme and a virtual damper concept to improve the performance while the vehicle is passing over a rough road.

The motivation for investigating vehicles' active suspension systems comes from the trade off between the control objectives of the suspension system. In this study a new fuzzy-logic approach is proposed in order to provide the suppression of vehicle-body bounce and acceleration while preserving the suspension's traveling limits. The controller is applied to a quarter-car model and numerical results are given to illustrate the performance of the proposed control strategy.

The rest of the paper is organized as follows. In Section 2, the vehicle model is presented. The proposed control method is explained in detail in Section 3. Next, the results of the application of the controller are given to reveal the success and the performance of the controller in Section 4. Finally, conclusions are drawn in the last section.

1 VEHICLE MODEL

Although passenger vehicles consist of four individual wheels, considering only one wheel is adequate when it comes to investigating the vertical dynamics and the main performance of an active suspension system as a quarter-car model, which is shown in Figure 1. In the diagram, m_1 and m_2 are the unsprung and sprung masses, respectively. The tire and suspension stiffnesses are denoted as k_1 and k_2. b_2 is the damping coefficient of the viscous damper and u corresponds to the control force that is produced by the actuator. y_0 is the road input to the tire. y_1 and y_2 are the absolute displacements of the unsprung and sprung masses, respectively. The suspension deflection is defined as $y_2 - y_1$. The pa-

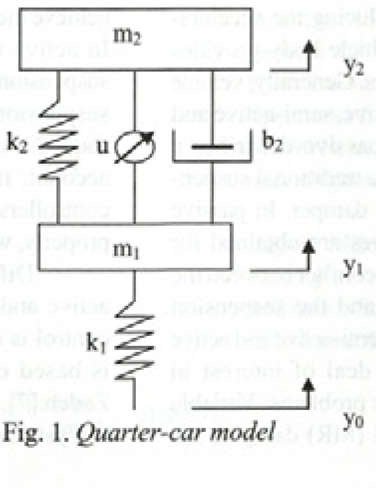

Fig. 1. *Quarter-car model*

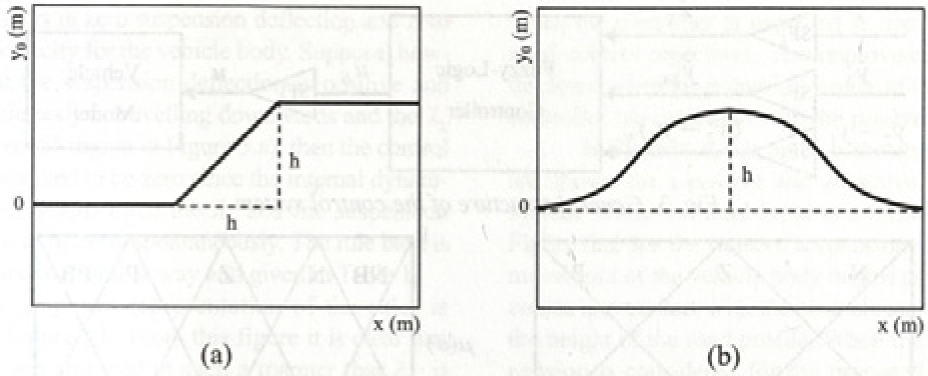

Fig. 2. *a) Limited-ramp road input b) Bump-road input*

rameters of the quarter-car model and the proposed controller are given in the Appendix.

The equations of motion for the quarter-car model are given below:

$$m_1\ddot{y}_1 + b_2(\dot{y}_1 - \dot{y}_2) + k_2(y_1 - y_2) + k_1(y_1 - y_0) = -u \quad (1)$$

$$m_2\ddot{y}_2 + b_2(\dot{y}_2 - \dot{y}_1) + k_2(y_2 - y_1) = u \quad (2).$$

In this study, the quarter-car model is subjected to the road inputs, as shown in Figure 2.a and 2.b. The vehicle model vibrates as it passes over the road profile with a constant velocity V during the first second of its travel. The bump-road equation [11] is:

$$y_0(t) = \begin{cases} h[1-\cos(8\pi t)]/2 \;; & 1 \le t \le 1.25 \\ 0 \;; & otherwise \end{cases} \quad (3).$$

2 CONTROLLER DESIGN

Fuzzy logic provides the ability to use the knowledge coming from experts, which is in linguistic form, according to fuzzy rules. Another property of fuzzy logic is its applicability to systems in which the exact mathematical model is not known. Because of these attractive features, it is used in a wide range of control applications.

There are three important steps in fuzzy-logic control: fuzzification, inference and defuzzification. In the first step the crisp variables are converted to fuzzy variables. In other words, membership functions are described for the input and output variables. In the second step the linguistic expressions are used to form the rules that constitute the rule base. In general, these rules are in the following form for a fuzzy controller with n inputs and a single output:

$$\text{IF } x_1 \text{ is } X_1 \text{ and } x_2 \text{ is } X_2 \text{ and } \ldots\ x_n \text{ is } X_n \text{ THEN } u \text{ is } U \quad (4).$$

Since the output values cannot be used directly, in the last step the fuzzy variables are converted to crisp values with an appropriate defuzzification method. In this study the centroid method, which is widely used in the literature, is used for the defuzzification of the fuzzy variables.

It is well known that conventional fuzzy-logic controllers operate like sliding-mode controllers with a boundary layer. It is thought that there exists a sliding line along the diagonal of the rule base and the control signal has opposite signs at the two sides. Therefore, evidence about the stability of the closed-loop control system can be obtained from an analogy between conventional fuzzy-logic control and sliding-mode control (Palm, [20]).

The aim of this study is to improve the ride comfort for passengers without causing any degradation in the suspension's working limits. Thus, a fuzzy-logic controller with three inputs and a single output is designed. The block diagram of the controller is given in Figure 3. The inputs are the derivative of the vehicle's vertical body displacement, $\dot{y}_{2N}$, the suspension deflection, $(y_2 - y_1)_N$, and a combination of these two inputs, $\lambda_N = \dot{y}_{2N} + \alpha(y_2 - y_1)_N$. Here, α is the weighting factor and the subscript N indicates that the variables are normalized.

Triangular membership functions are used for the fuzzy variables, as shown in Figure 4. NB, N, Z, P and PB denote negative big, negative, zero, positive, and positive big, respectively.

The input and output membership functions are defined on the [-1,1] closed interval, and the scaling factors (*SF*s) are used in order to map the crisp values to the corresponding fuzzy values. The relationships between the normalized and actual values

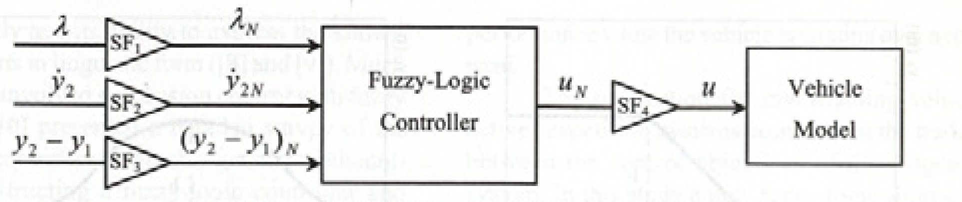

Fig. 3. *General structure of the control system*

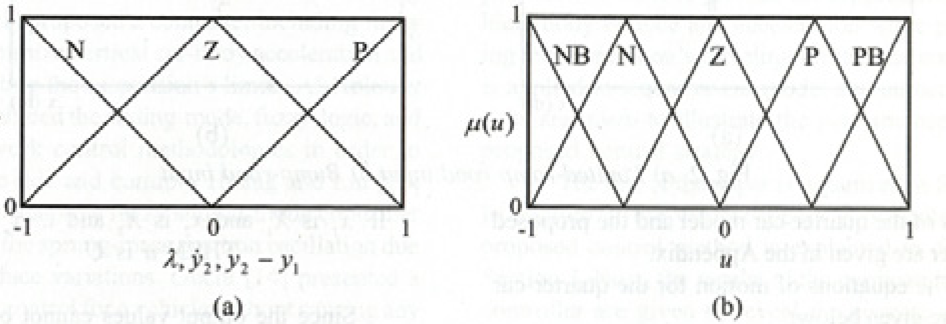

Fig. 4. *Membership functions a) input variables b) output variable*

are shown below.

$$\lambda_N = \lambda SF_1 \tag{5}$$

$$\dot{y}_N = \dot{y}_2 SF_2 \tag{6}$$

$$(y_2 - y_1)_N = (y_2 - y_1) SF_3 \tag{7}$$

$$u = u_N \, SF_4 \tag{8}$$

Since the aim of this study is to improve the ride comfort without causing any degeneration in the suspension's working limits, the input variable $\lambda_N = \dot{y}_{2N} + \alpha (y_2 - y_1)_N$ plays an important role in the construction of the rule base. Rendering this variable zero will fulfil the aim of the study. According to the sign of the input variables, there are six regions on the $(y_2 - y_1)_N$ vs. $\dot{y}_{2N}$ plane, as depicted in Figure 5.a. When λ_N takes negative values, that means either a negative suspension deflection exists or the suspension deflection tends to be negative because of the large vertical vehicle-body acceleration. Thus, during this time the control force should be positive, which pushes the vehicle body upwards. Similarly, for the positive values of λ_N, a negative force should be applied to the vehicle body. When λ_N assumes approximately zero values, which agrees with the design requirements, the control inputs are approximately zero. For the nonzero values of λ_N, the other two inputs of the fuzzy controller give information about the location of the system states. For example, if all the inputs are positive (1st region in Figure 5.a), i.e., a positive suspension deflection exists and the vehicle body is travelling upwards, then the control input is selected to be negative big. This choice of control input forces the vehicle body to travel downwards,

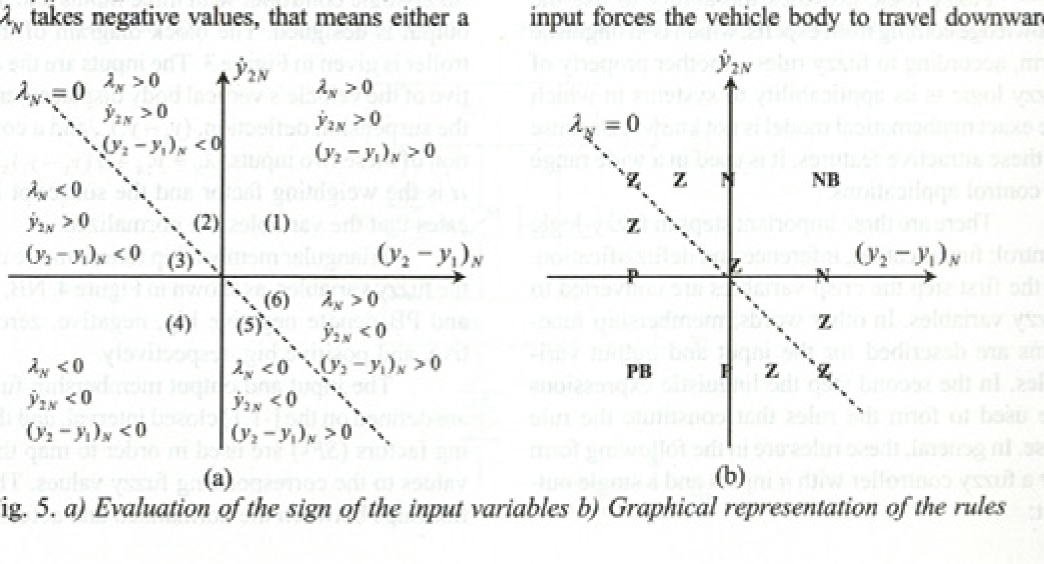

Fig. 5. *a) Evaluation of the sign of the input variables b) Graphical representation of the rules*

which results in zero suspension deflection and zero vertical velocity for the vehicle body. Suppose, however, that the suspension deflection is positive and the vehicle body is travelling downwards and the λ_N is negative (5th region in Figure 5.a), then the control input is selected to be zero since the internal dynamics of the system force the λ_N and the suspension deflection to be zero, spontaneously. The rule base is constructed in a similar way and given in Table 1.

A graphical representation of the rules is given in Figure 5.b. From this figure it is clear that the rules are arranged in such a manner that λ_N is rendered to be zero by applying certain control inputs. Next, the states are kept in the region where $\lambda_N = 0$ and the internal dynamics of the system render the suspension deflection and the vertical velocity of the vehicle body to be zero. Thus, all the states of the system are regulated to zero by the constructed rule base. In fact, it is possible to write 27 rules when three inputs are used. However, some of them are not physically realizable. For instance, if the suspension deflection and the derivative of the vertical body displacement are both negative, the first input variable, λ_N, cannot have a positive value. Thus, certain input combinations are not used during the construction of the rule table, which reduces the size of the rule base and decreases the computation time.

3 RESULTS

The controller is focused on the body bounce, the body acceleration and the suspension deflection. Thus, the controller is expected to improve the related control objectives. The improvements can be disclosed when the numerical results of the proposed controller are compared with the passive results.

In Figure 6.a, 6.b, and 6.c, the time responses are shown for a passive and an active suspension system, while the road input is a limited ramp. In Figure 6.a, for the passive suspension, the vertical movement of the vehicle body begins as the vehicle comes into contact with the obstacle and overshoots the height of the road profile. When the active suspension is considered for the proposed controller, the sprung mass softly settles on its steady value, as seen in the same figure. If the suspension deflection is also taken into account, it is clear that the suspension regains its original position, as seen in Figure 6.c. The suspension deflection reaches zero as the sprung mass settles. Thus, there is no permanent deflection in the suspension. The body acceleration is also decreased by the proposed control strategy, as shown in Figure 6.b.

In order to verify the performance of the proposed controller a typical bump-road input is also applied to the vehicle model and the time responses are given in Figure 7. It is clear that the magnitudes are reduced for the vertical body displacement and the vertical body acceleration, which indicates that ride comfort is improved greatly. It is also clear that the suspension working space is preserved for this road disturbance.

In Figure 8.a, and 8.b, the frequency responses for the vehicle body displacement and

Table 1. *Rule base for the control input u*

Input			Output
λ	$\dot{y}_2$	$y_2 - y_1$	u
P	P	P	NB
P	P	Z	N
P	P	N	Z
P	Z	P	N
P	N	P	Z
Z	P	N	Z
Z	Z	Z	Z
Z	N	P	Z
N	P	N	Z
N	Z	N	P
N	N	P	Z
N	N	Z	P
N	N	N	PB

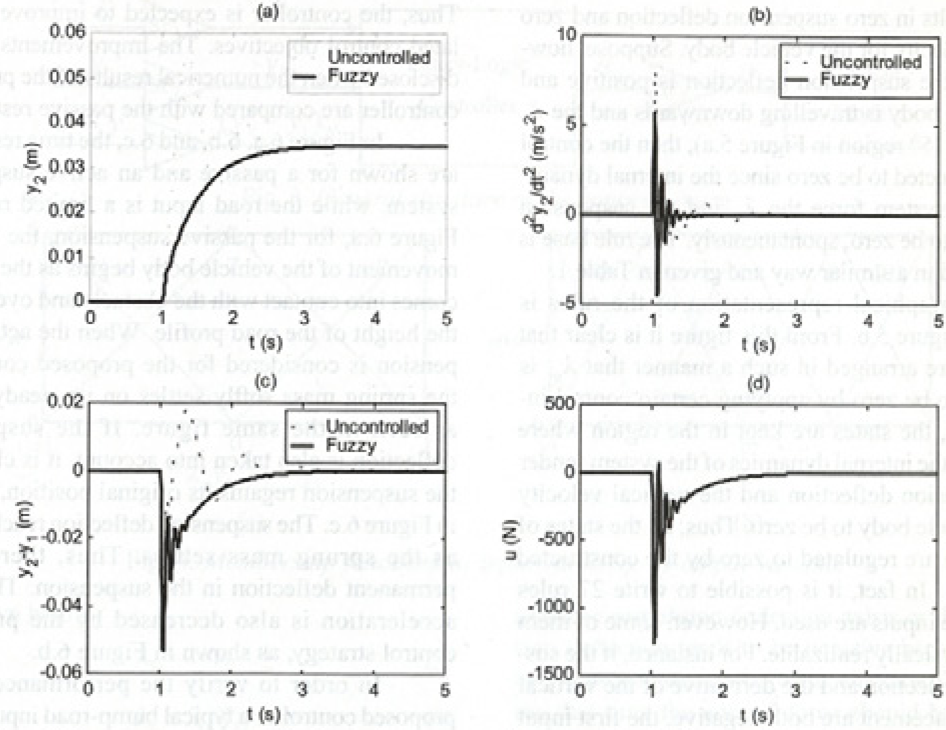

Fig. 6. *Time responses for the limited-ramp road input; a) Body bounce b) Body acceleration c) Suspension deflection d) Control force*

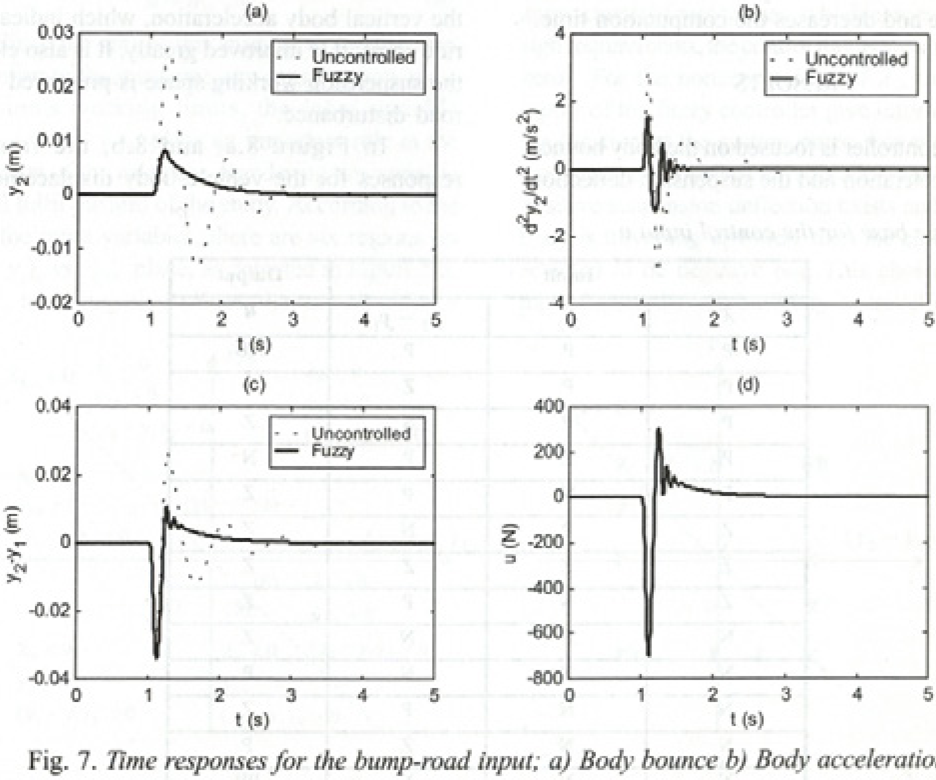

Fig. 7. *Time responses for the bump-road input; a) Body bounce b) Body acceleration c) Suspension deflection d) Control force*

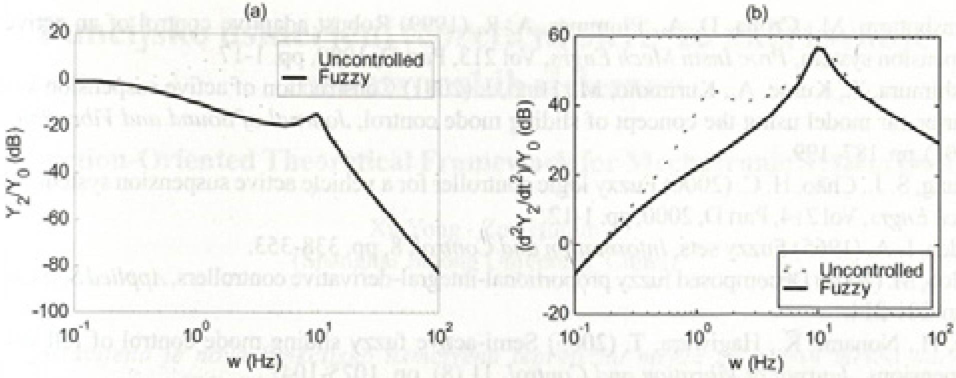

Fig. 8. *Frequency responses; a) Body bounce b) Body acceleration*

acceleration are shown for passive and active suspension systems. It is clear that the resonance frequency of the body on which the passengers are positioned is suppressed very well by the proposed controller around 1 Hz. The magnitudes are also reduced across a wide frequency range, which indicates that the ride comfort is improved.

To test the performance of the controller experimentally, an accelerometer will be used to sense the vertical motion of the vehicle body and LVDT sensors will be used to measure the suspension's working space. These data will be the inputs to microprocessors, which are programmed using the proposed fuzzy-logic control algorithm. Finally, the control inputs will be applied to the vehicle body using linear motors that will be used as actuators.

4 CONCLUSION

In this study a multiple-input, single-output fuzzy-logic controller is proposed in order to improve the ride comfort of passengers without causing any permanent reduction in the suspension's working space. The derivative of the vertical body displacement, the suspension deflection, and the combination of these two variables are used as inputs, and the controller force is the output. Although the fuzzy-logic controller has three inputs, only thirteen rules are required in order to fulfill the aim of the study. Time responses show that the vehicle body settles smoothly and that the suspension's working space is preserved. Finally, the frequency responses also showed that the ride comfort of the passengers was greatly improved.

5 APPENDIX

Numerical parameters of the quarter-car model

$m_1 = 36$ kg
$m_2 = 240$ kg
$b_2 = 980$ Ns/m
$k_2 = 16000$ N/m
$k_1 = 160000$ N/m
$V = 72$ km/h
$h = 0.035$ m

Numerical parameters of the proposed controller

SF1 = 1/0.3
SF3 = 1/0.1
$\alpha = 1$
SF2 = 1/0.3
SF4 = 6000

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Prejeto: Received: 5.6.2006
Sprejeto: Accepted: 25.10.2006
Odprto za diskusijo: 1 leto
Open for discussion: 1 year