Fuzzy Sliding Mode Control for applying to active vehicle suspentions

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Abstract*:-* Suspension system is an important part of the car design, because it influences both the comfort and safety of the passengers. Controlling of Suspension system has special difficulties since this system is highly nonlinear, essentially unstable systems and energy demands of the system. In particular, this article is focused on experiments with the physical model of semi-active quarter-car suspension that using the method of fuzzy sliding mode which uses the fuzzy logic techniques to adjust the control gains that occur under the sliding mode.

Functionality of the modification was verified taking various experiments and the results show that the proposed fuzzy controller robustly is efficiency. The computation of the command force to apply to the system in order to control the suspension was based on the fuzzy logic theory for which three essential steps were developed: fuzzification, inferences, and defuzzification. To put into evidence the efficiency and the performances of such a control system, we have compared the results obtained through the sliding mode technique solely, then through the combination of the fuzzy logic theory and the set up by the sliding mode, and the fuzzy sliding mode.

Key-Words: Fuzzy Logic, Active Control, Vehicle Suspension, Sliding Mode.

1. INTRODUCTION

There are three type of vehicle suspension: passive, semiactive and active. Differences depend on the operation mode to improve vehicle ride comfort, vehicle safety, road damage minimization and the overall vehicle performance. Normally, conventional passive suspensions are effective only in a certain frequency range and no on-line feedback action is used. Thus, optimal design performance cannot be achieved when the system and its operating conditions are changed. On the contrary, active suspensions can improve the performance of the suspension systems over a wide range of frequency and can adapt to the system variations based on on-line changes of the actuating force. Nowadays, increased competition on the automotive market has forced companies to research alternative strategies to classical suspension systems. The basic function of the vehicle suspension is to support the weight of the car, maximize the friction between the tires and the road surface, provide steering stability with good handling and ensure sufficient comfort of the passengers. In order to improve handling and comfort performance instead of a conventional static spring and damper system, semi-active and active systems are being developed and also it is essential to conceive optimized suspension systems [1], [2]. As passive suspensions are not always able to meet such requirements, researchers were rather interested rather interested in the conception of semi-active or active suspensions which could change their control parameters in function of the road conditions. An ideal vehicle suspension system should have the capability to reduce sprung mass displacement and acceleration, and provide adequate suspension deflection to maintain tyre-terrain contact. Active suspension system with addition actuator to generate the control force for vibration suppression is a right choice to achieve better suppression effect. Generally, it is difficult to establish or identify an accurate dynamic model of a complicated hydraulic suspension system for designing optimal controller [3]–[7]. Fuzzy logic control law can be designed based on some knowledge or without any knowledge about the control system. In addition, an appropriate fuzzy logic controller can overcome the environmental variation during operation processes. Therefore, it has been employed in the field of active suspension system. Ro *et al.* [8] developed a fuzzy logic algorithm for an active ride comfort of a quarter-car model. Yester and Mcfall [9] and Cherry and Jones [10] employed fuzzy logic strategy for controlling an automotive suspension incorporating active elements. Huang and Chao [11] proposed a gery fuzzy control scheme to remove tyre deformation from the control variable using a grey predictor for improving the control performance. However, the design of a traditional fuzzy controller depends fully on an expert or the experience of an operator to establish the fuzzy rules bank. There is no guide rule for designing the fuzzy rules bank and parameters. A time-consuming adjusting process is required to achieve the specified control performance. Thereafter, self-tuning algorithms were introduced into fuzzy controller to adjust fuzzy parameters and improve the control performance based upon a specified performance index [12], [13]. Rao and Prahlad [14] proposed a tuneable fuzzy controller for an active suspension system. However, they need a complicated learning mechanism or a specific performance decision table designed by trial-and-error. Its application still presents certain difficulty. The number of rules increases exponentially with respect to the number of dimensions. In addition, there is still lacking of theoretical modeling and analysis for the fuzzy logic control (FLC) stability and robustness problems. The commercial industrial application is hesitated and progressed slowly. Hence, the robustness advantage of a sliding mode control was introduced into the fuzzy controller in recent researches. For example, fuzzy sliding mode control [15]–[17] and adaptive fuzzy control [18], [19] were proposed to achieve the stability property and tracking error analysis of a FLC. Yi and Chung [20] employed fuzzy control to substitute the boundary layer term of a sliding mode in order to improve the chattering behavior of a sliding mode control. Hwang and Lin [21], Palm [15] and Wang [22] employed a switch function as the fuzzy input variables and proposed a fuzzy sliding mode controller. Lu and Chen [23] extended this approach and developed a self-organizing fuzzy sliding mode controller to smooth the chattering phenomenon. Lo and Kuo [24] combined the decoupling and sliding mode concepts into fuzzy controller. Wang [22] and Su and Stepanenko [25] proposed a globally stable adaptive controller based on Lyapunov stability theory. They employed a fuzzy system adjusted by an adaptive law to approximate an optimal controller to a specified accuracy. However, this kind of direct adaptive law is limited to nonlinear system with constant control gain. After that, Chai and Tong [26] proposed a fuzzy direct control scheme by using a fuzzy system to approximate an optimal controller that was designed based on the assumption that all of the dynamics in the system were known. Then, a fuzzy sliding controller was added to the adaptive controller for compensating the uncertainties and smoothing the control signal. Ting *et al.* [27] employed the fuzzy sliding mode control to design active suspension system for investigating the ride comfort. However, these approaches still depend on a certain model for a sliding mode to operate. In addition, the fuzzy rule bank design and calculation are still complicated. The number of rules was increased exponentially with respect to the number of fuzzy subsets. Kim and Lee [16] introduced a variable to reduce half of the dimension of the input vector and the number of fuzzy rules. However, it still needs nominal system model and the estimated value of uncertainty upper bound. Those factors hinder its applications and implementation. This article deals in the first section with the performances that are obtained on this type of model by the method of fuzzy sliding mode which uses, in the present case, the fuzzy logic techniques to adjust the control gains that occur under the sliding mode.

2. EXPLANATION AND FORMULATION OF QUARTER-CAR MODEL

It is well known that certain implementation problems cannot be anticipated from the computer simulation study. A quarter-car two-degrees-of-freedom (DOF) active suspension system is designed and built for investigating the dynamic performance and control effect. This hydraulic suspension system schema is shown in Fig. 1. The suspension mechanism includes an assembly of spring and mass, and a hydraulic control loop. The first hydraulic servo system is used to generate various road surface conditions. Hydraulic flow rate is regulated by a proportional flow valve. An optical linear scale and a linear potentiometer are employed to measure the sprung mass road surface vertical displacements, respectively. An accelerometer is installed on sprung mass to measure the acceleration for evaluating the riding comfort. The I/O data interface unit includes a PCL-812 analog to digital (A/D) card, a PCL-726 D/A card and a PCL-833 encoder card. The PCL-833 card has onboard encoders to count the output signal of the optical linear scale, which was installed on the vehicle body to measure the vertical displacement of the sprung mass.APC Pentium is used to handle all the input/output (I/O) data of the whole system and to control the vehicle sprung mass oscillation amplitude. In order to evaluate the dynamic response and control performance of this active suspension system, the two-DOF dynamic model of this quarter car system is employed. The basic assumptions are that the tyre always contacts with the road surface and the function of the tyre is simulated by a spring with spring constant and unsprung mass. The sprung mass of the vehicle body is considered as rigid body. The spring, damper, and actuator between sprung mass and unsprung mass constitute an active suspension system as Fig. 2, where and are measured variables representing the sprung mass displacement and the displacement of tyre axis, respectively.

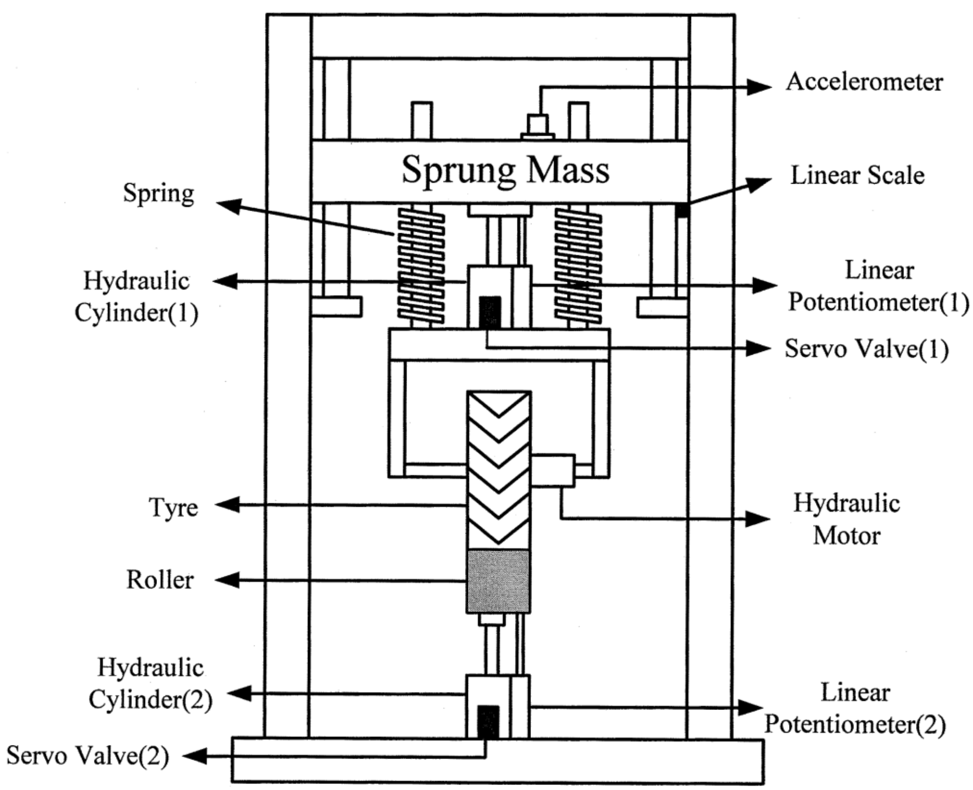

Fig. 1. Schema of a hydraulic active suspension system

Also, we can see the Active suspention system model in Fig. 2 and Control strategy by fuzzy sliding mode in the Fig. 3.

The matrix equation of the motion for the vehicle body is given by[28]:

$$\dot{x} = AX + BU + EW$$

X is the state vector with:

$$x_1 = Z_s - Z_{us}$$
$$x_2 = \dot{Z}s$$
$$x_3 = Z_{us} - Z_r$$
$$x_4 = \dot{Z}u$$

$$A = \begin{pmatrix} 0 & 1 & 0 & -1 \\ -k_s/M_s & -b_s/M_s & 0 & b_s/M_s \\ 0 & 0 & 0 & 1 \\ k_s/M_u & b_s/M_u & -k_t/M_u & -b_s/M_u \end{pmatrix}$$

And also,

$$B = (0, 1/M_s, 0, -1/M_u)^T$$
$$E = (0, 0, -1, 0)^T$$
$$W = \dot{Z}r$$
$$U = f_a$$

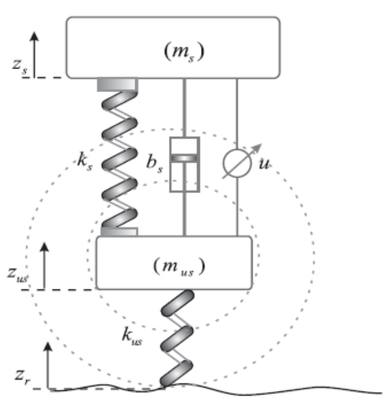

Fig. 2. Active suspention system

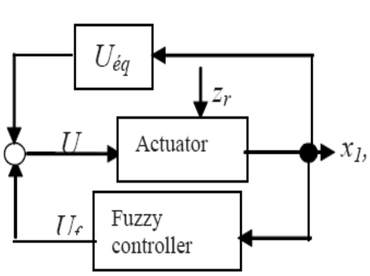

Fig. 3. Control strategy by fuzzy sliding mode

Nomenclature and parameter values in a quarter car model that was studied in our research had the following features:

Model parameters	symbol	values	unit
Spring mass	Ms	320	Kg
Suspension stiffness	k_s	18000	N/m
Suspension damping rate	b_s	1000	N/(m/sec)
Wheel assembly mass	m_{us}	40	Kg
Tire stiffness	k_{us}	200000	N/m
Normalizing factor	u_{max}	1000	N

3. Controller Design Scheme

According to what was said in the first of the paper, for optimizing the system three criteria that are comfort, road-holding, and suspension travel were selected. The performance index can hence be written as follows [29]:

$$J = E\{0.5 \int_0^{\infty} (q1(Zs - Zus)^2 + q2(Zus - Zr)^2 + q3\,(\dot{Z}s)^2 + q4(\dot{Z}u)^2 + \rho U^2)\}$$

As the general form of the performance index is:

$$J = E\{(X^T QX + 2X^T NU + U^T RU)dt\}$$

We can find a symmetric matrix (P) in the Riccati's equation:

$$A^T P + PA + Q - (PB + N)R^{-1}.(B^T P + N^T) = 0$$

For minimizing linear performance index J: U=– G.X: U: Control force

G: Control gain matrix: $G = B^{-1}(N^T + B^T P)$.

We assume that it is system disturbance, due to road surface velocity$\dot{Z}r$, and that this is a white noise:

E[$\dot{Z}r$(t)]= 0 and E[$\dot{Z}r$(t)$\dot{Z}r$(t+ζ)]= HV™ (δ).

H: A parameter related to the roughness of the road

V: Speed of the vehicle
δ : Dirac's function
The spectrum density of the road profile reads then:

$$\Phi_{zr}(\omega)\ HV / \omega^2 = 0$$

3.1. Sliding mode control

We want to bring state trajectory of a system towards the sliding surface by linear control.
We define sliding surface in following form: [30]

$$S(x1, x2) = x2 + \lambda x1 ,\ \lambda > 0$$

Control force U has two parts:

$$U = U\acute{e}q + Ug$$

Uéq:The equivalent control force,as defined by Utkin [34]
Ug:The singular one
In ideal sliding mode, the expression of surface and its derivative form are nulls, thus:
$U\acute{e}q = -B^{-1}[AX + EW]$ or $U\acute{e}q = -L^{-1}\ [a_1\ x_1 + (a_2 + \lambda)\ x_2]$
Where:

a_1: –ks/ Ms
a_2: –bs/ Ms
L: a gain of the control related to Ms
$L=\sqrt{(bmin, bmax)}$
bmin:empty vehicle
bmax: loaded vehicle

L also can be obtained from the values of a limited interval defined by:

$\beta^{-1} < L/b < \beta$
$\beta=\sqrt{(bmin, bmax)}$.

Ug guarantee convergence towards the sliding surface and is defined by following form:

$$Ug = -L^{-1}K \,.\, \mathrm{sgn}(S)$$

K satisfying the sliding condition [31],[32]

3.2. Fuzzy sliding mode control

The fuzzy sliding mode control is used to better the problem of the main inconvenience of the sliding mode, which damage actuators and has bad effect in system's function. We need the application of the principle of self adaptation of the gains which occur at the force control in the Fuzzy sliding control. Figure 3 summarizes the control principle of the fuzzy sliding mode using a self-regulator [33]:

$$U = U\acute{e}q + U f$$

Uéq is calculated in the same way as for the sliding mode solely. And $U f = GU.\, upf$ (force control calculated by the fuzzy logic theory [30]) *upf* is calculated with the first controller (Fig. 4).

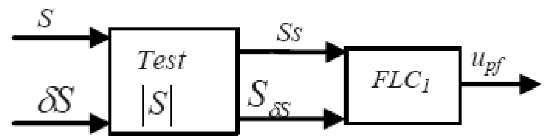

Fig. 4. Calculation steps of *upf*

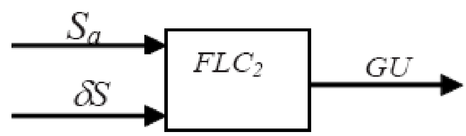

Fig. 5. Calculation of *GU*

The variation ™*S* is such as $\delta S(t)=S(t)-S(t-T)$ and the average $S_a(t)$[30] :

$$S_a(t)=\frac{1}{N}\sum_{i=0}^{N-1} S(t-iT)$$

Where:

T :a sampling period
N:the number of samples: $N=t/T$

The first fuzzy controller has two inputs [33]:

$Ss = S* GS$ and $S_{\delta s} = S* CGS$

4. EXPERIMENT AND RESULT

GS and *CGS* are gains that are conditioned by the evolution of the sliding surface. The center of gravity method is used to defuzzify the inferred output *upf*. The gain *GU* is obtained from the output of a 2nd fuzzy controller (see Fig. 5). Defuzzification process allows the obtention of the value of gain *GU*.
For comparison and validation purposes of our results with what is available in literature, we have deliberately taken an excitation of the road profile, under a sinusoidal form.

$$Zr(t) = \frac{CK\sin(wt)}{(\frac{w}{2\Pi V})^{2.5}}$$

Where:

ω = 7.7 rad/s
CK: function of the quality of the road
V = 30 m/s
$\lambda = 10;\ K = 70;\ \hat{b}^{-1}$ =250

Figs. 6 and 7 illustrate the results obtain by optimal control, sliding mode, and fuzzy sliding mode.

the sliding mode respect the suspension travel better. (see Fig. 6)

Both fuzzy sliding mode and the optimal control have very close responses. Therefore we can declare that the results from optimal control and fuzzy sliding mode were very similar.

For a slightly higher cost, the setting up by fuzzy sliding mode produces better performances in terms of comfort, whereas the sliding mode is more appropriate to the functioning space of suspension. Furthermore, let us notice, that by deteriorating some 30% of the intrinsic characteristics of the suspension studied, (by increasing the mass of the frame and decreasing by 30% the damping stiffness) we could also check the strong validity of these control methods.

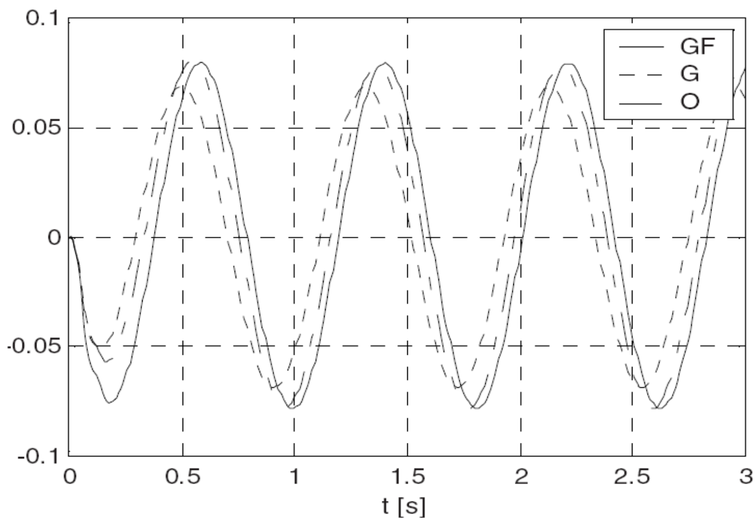

Fig. 6. Suspension travel (GF = Fuzzy Sliding, O = Optimal control)

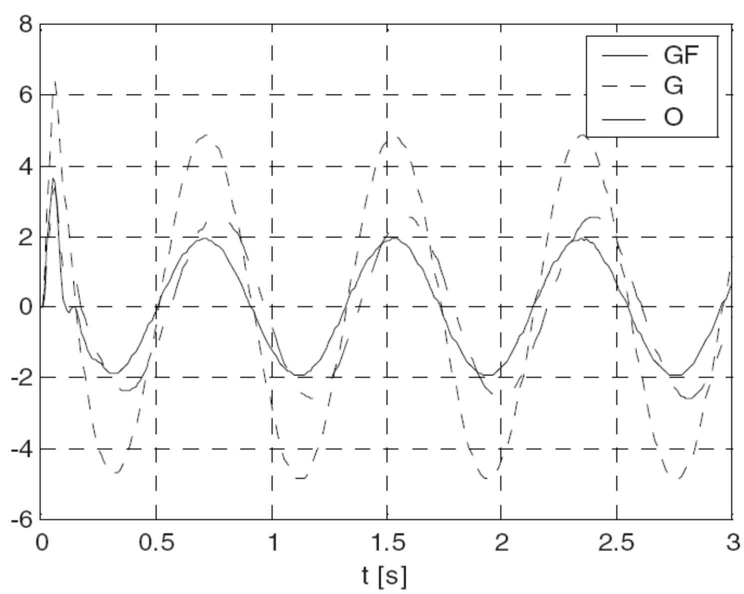

Fig. 7. Sprung mass acceleration G = Sliding, O = Optimal control) [Vertical axes is acceleration mass(Ms)]

4.1. Vehicle Riding on a Concave–Convex Road Profile

When a vehicle riding on a rough concave–convex road with a 40-mm height change, the sprung mass dynamic position variation with this hydraulic active suspension system are shown in Fig. 8(a) by using The fuzzy sliding mode control scheme. The solid line exhibits the road profile, the dotted line depicts the passive displacement of the sprung mass and the dashed line denotes the sprung mass position variation with active suspension system. The maximum displacement of the sprung mass with The fuzzy sliding mode control active suspension system is within 3.5 mm. The sprung mass acceleration and control voltage are shown in Fig. 8(b) and (c), respectively. The solid line exhibits the active control spring mass acceleration dynamics, and the dotted line depicts the passive system sprung mass acceleration, respectively. The root-meansquare (RMS) values of the acceleration oscillation amplitudes are 27.47 and 7.77 mm/s, respectively, for passive and active system.

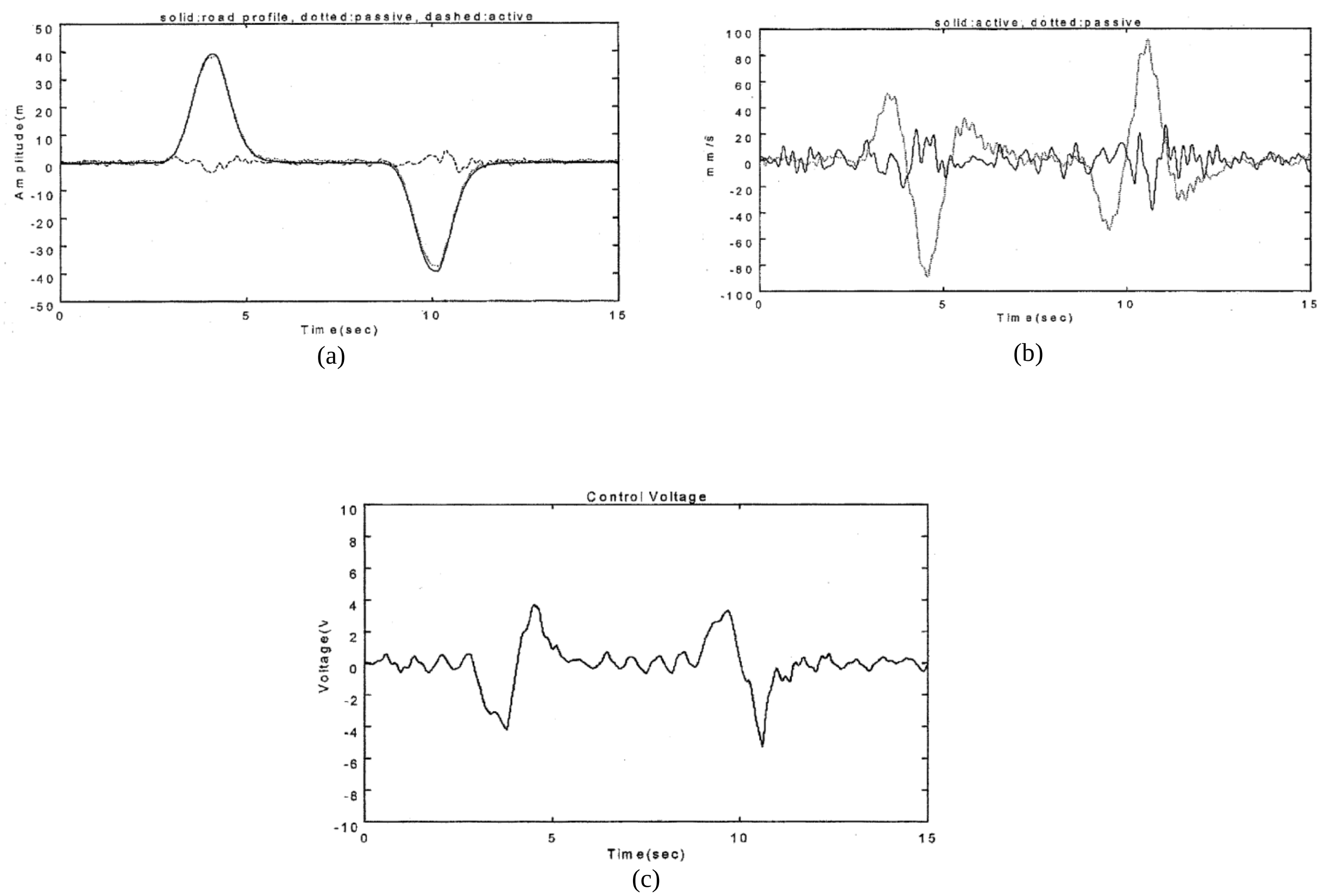

Fig. 8. Sprung mass (a) position variation, (b) acceleration response, and (c) control voltage history for riding on a concave-convex road by using The fuzzy sliding mode control.

4.2. Vehicle Riding on a Rough Road With Random Disturbance

When a vehicle travelling on a rough road with a random amplitude, the sprung mass position and acceleration dynamic responses of this quarter-car suspension system are shown in Fig. 9(a) and (b), respectively. It can be observed that the maximum sprung mass position oscillation is maintained within 3.0 mm and the acceleration oscillation amplitude is within 25 mm/s . The root-mean-square (RMS) value of the position and the acceleration oscillation amplitudes are 1.04 mm and 8.19 mm/s, respectively. The control voltage is depicted in Fig. 9(c). The above experimental results show that this novel control strategy has suppressed effectively the sprung mass position oscillation amplitude and reduced the acceleration amplitude, too.

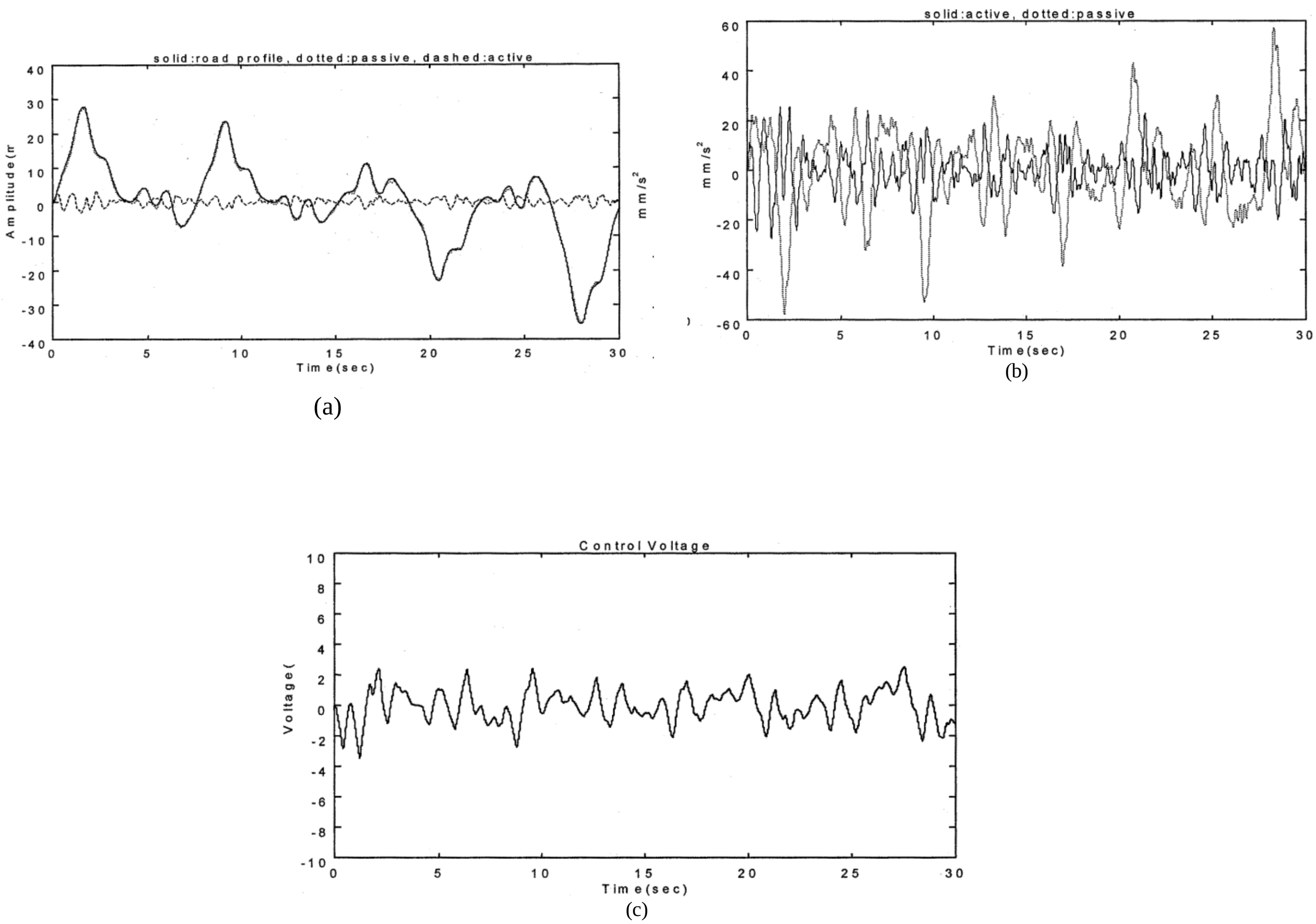

Fig. 9. Sprung mass (a) position variation, (b) acceleration response, and (c) control voltage history for vehicle riding on a rough road with random disturbance by using The fuzzy sliding mode control.

Conclusions

The fuzzy logic in sliding mode control was proposed to design a controller for suspension system of a quarter vehicles in order to improve the performance of system. Also the results from optimal control and fuzzy sliding mode were very similar and

the results show that among the inconveniences that are in common in these methods, when the order of the system to control is high selection the of sliding surface for the fuzzy mode and the fuzzy sliding mode is very complex.

Also we need to use the rules of automatism in order to determine the computation coefficients by sliding mode, which is very difficult.

High frequency commutations of the actuator due to chattering phenomenon have negative effect on controller. And Fuzzy sliding mode control enables to fix the chattering phenomenon.

As the optimal control offers good performances only for the system nominal Values, The sliding and fuzzy sliding methods are very strong to be compared with it.

REFERENCES:

[1] Jamal Ezzine, Francesco Tedesco. H_∞ Approach Control for Regulation of Active Car Suspension. *INTERNATIONAL JOURNAL OF MATHEMATICAL MODELS AND METHODS IN APPLIED SCIENCES*. 2009.

[2] Katerina Hyniova, Antonin Stribrsky, Jaroslav Honcu and Ales Kruczek. Active Suspension System with Linear Electric Motor. *WSEAS TRANSACTIONS on SYSTEMS*. 2009.

[3] N. Louam, D. A. Wilson, and R. S. Sharp, "Optimization and performance enhancement of active suspensions for automobiles under preview of the road," *Vehicle Syst. Dyna.*, vol. 21, no. 12, pp. 39–63, 1992.

[4] R. G. M. Huisman, F. E. Veldaus, H. J. M. Voets, and J. J. Kok, "Optimal continuous time control strategy for active suspension with preview," *Vehicle Syst. Dyna.*, vol. 22, no. 1, pp. 43–55, 1993.

[5] M. B. A. Abdel-Hady, "Active suspension with previewcontrol," *Vehicle Syst. Dyna.*, vol. 23, pp. 1–13, 1994.

[6] R. G. Langlois, D. M. Hanna, and R. J. Anderson, "Implementing previewcontrol on an off-road vehicle with active suspension," *Vehicle Syst. Dyna.*, vol. 20, pp. 340–353, 19 912.

[7] T. Yoshimura, K. Edokoro, and M. Ananthanarayana, "Active suspension model for rail/vehicle systems with preview and stochastic optimal control," *J. Sound Vibrat.*, vol. 166, no. 3x, pp. 507–519, 1993.

[8] P. I. Ro, C. Kim, and H. Kim, "Active suspension using fuzzy logic control," in *Proc. Amer. Control Conf.*, 1993, pp. 2252–2253.

[9] J. L. Yester and R. H. McFall, "Fuzzy Logic controller for active suspension," in *Proc. Soc. Automotive Engineers*, 1992, paper P-260, pp. 259–270.

[10] A. S. Cherry and R. P. Jones, "Fuzzy logic control of an automotive suspension systems," *Proc. Inst. Elect. Eng.D: Control Theory Application*, vol. 142, no. 2, pp. 149–160, 1995.

[11] S. J. Huang and H. C. Chao, "Fuzzy logic controller for a vehicle active suspension system," Proc. Inst. Mech. Eng., Part I: J. Automobile Eng., vol. 214, pp. 1–12, 2000.

[12] M. Maeda and S. Murakami, "A self-tuning fuzzy controller," *Fuzzy Sets Syst.*, vol. 47, pp. 13–21, 1992.

[13] W. Z. Qiao,W. P. Zhung, and T. H. Heng, "AS rule self-regulating fuzzy controller," *Fuzzy Sets Syst.*, vol. 47, pp. 13–21, 1992.

[14] M. V. C. Rao and V. Prahlad, "A tuneable fuzzy Logic controller for vehicle active suspension system," *Fuzzy Sets Syst.*, vol. 85, pp. 11–21, 1997.

[15] R. Palm, "Robust control by fuzzy sliding mode," *Automatic*, vol. 30, no. 9, pp. 1429–1437, 1994.

[16] S.W. Kim and J. J. Lee, "Design of a fuzzy controller with fuzzy sliding surface," *Fuzzy Sets Syst.*, vol. 71, pp. 359–367, 1995.

[17] H. Lee, E. Kim, H. J. Kang, and M. Park, "Design of a sliding mode controller with fuzzy sliding surfaces," *Proc. Inst. Elect. Eng.D: Control Theory Applicat.*, vol. 145, no. 5, pp. 441–418, 1998.

[18] L. S. Chen andW. L. Chen, "Robust adaptive sliding mode control using fuzzy modeling for an inverted pendulum system," *IEEE Trans. Ind. Electron.*, vol. 45, pp. 297–306, Mar. 1998.

[19] F. J. Lin and S. L. Chiu, "Adaptive fuzzy sliding mode control for PM synchronous servo motor drives," Proc. Inst. Elect. Eng. D: Control *Theory Applicat.*, vol. 145, no. 1, pp. 63–72, 1998.

[20] S. Y. Yi and M. J. Chung, "Robustness of fuzzy logic control for anuncertain dynamic system," *IEEE Trans. Fuzzy Syst.*, vol. 6, Apr. 1998.

[21] G. C. Hwang and S. C. Lin, "A stability approach to fuzzy control design for nonlinear systems," *Fuzzy Sets Syst.*, vol. 48, pp. 269–278, Apr. 1992.

[22] L. X.Wang, "Stable adaptive Fuzzy control of nonlinear systems," *IEEE Trans. Fuzzy Syst.*, vol. 1, pp. 146–155, Feb. 1993.

[23] Y. S. Lu and J. S. Chen, "A self-organizing fuzzy sliding mode controller design for a class of nonlinear servo systems," *IEEE Trans. Ind. Electron.*, vol. 41, pp. 492–502, July 1994.

[24] J.-C. Lo and Y.-H. Kuo, "Decoupled fuzzy sliding mode control," *IEEE Trans. Fuzzy Syst.*, vol. 6, pp. 426–435, June 1998.

[25] J. Su and Y. Stepanenko, "Adaptive control of a class of nonlinear systems with fuzzy Logic," *IEEE Trans. Fuzzy Syst.*, vol. 2, pp. 285–294, Nov. 1994.

[26] T. Chai and S. Tong, "Fuzzy direct adaptive control for a class of nonlinear systems," *Fuzzy Sets Syst.*, vol. 103, pp. 397–387, 1999.

[27] C. S. Ting, T. H. S. Li, and F. C. Kang, "Design of Fuzzy controller for active suspension system," *Mechatron.*, vol. 5, no. 4, pp. 365–383, 1995.

[28] Ahmad Akbari, Milad Geravand. *Output feedback constrained H∞ control of active vehicle suspensions*. The 2nd IEEE International Conference on Advanced Computer Control(ICACC 2010), Shenyang, China, 27th-29th March 2010.

[29] Hac A. Suspension optimization of a 2 DOF vehicle model using a stochastic optimal control technique. J. Syst. Vehicle, Vol. 100(3), pp. 343–357. 1985.

[30] Nadhira Kheznadji *Messaoud-Nacer*, *Performances of Vehicles'Active Suspensions, Springer Science* + *Business Media* B.V. 2009.

[31] Slotine J.J. Sliding controller design for nonlinear systems. Int. J Control, Vol. 43, pp. 1631–1651. 1984

[32] Slotine J.J. Adaptative sliding controller synthesis for non linear systems. Int. J. Control, Vol. 43, pp. 1631–1651. 1986

[33] Chen-Sheng Ting, Tzuu-Hseng S Li and Fan Chu Kung. Design of fuzzy controller for active suspension control system. Mechatronics, Vol. 5(2), pp. 365–383. 1995

[34] Utkin V. Variable structure systems with sliding modes. *IEEE Transactions on automatic control*, Vol. AC-22, (2).1968.