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A New Fuzzy Sliding Mode Controller with Auto-adjustable Saturation Boundary Layers Implemented on Vehicle Suspension

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A B S T R A C T

This study develops a fuzzy sliding mode controller (FSMC) based on a variable boundary layer. A fuzzy inference mechanism has been used to tune the thickness of the boundary layers of the controller online. To lower the rate of calculation of the controller, a minimum rule base has been used. The aim of this paper is to design a controller which is able to remove the chattering and maintains the robustness of controller simultaneously. To prove the effectiveness of this method, a simulation has been done using MATLAB/SIMULINK. In this simulation, the results of 3 controllers, FSMC with auto-adjustable boundary layers, FSMC with fixed boundary layers, and FSMC with sign function are compared. The results of the simulation confirm that the performance of fuzzy sliding mode controller based on auto-adjustable boundary layer method is superior to the fixed boundary layer method

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1. INTRODUCTION

With regard to dramatic increase in demand for vehicle ride reliability and comfort, the research on vibration control has been the center of attention of the researchers. The main aim of a suspension system is to reject the disturbances excited by the road [1]. Three major suspension systems are passive, semi-active, and active suspensions. These suspension systems mainly focus on enhancing vehicle ride comfort, road holding, vehicle safety, and general vehicle performance [2]. A lot of research has been done to improve the performance of the vehicle suspension systems [1-3].

Controllers have become an essential part of modern society. They are used in different applications such as rocket fires, the space shuttles, self-guided vehicles, and robots. The main purpose of designing a controller is to obtain a desired output with desired performance. Some measurements of performance are transient response, steady-state error, stability, robustness, and disturbance rejection [3]. Controllers are devices which can sense the information from the plant or process (i.e. a suspension system) and use this information to reach the desired performance [4].

The Variable Structure System (VSS) with Sliding Mode Control (SMC) was first used by Russian researchers in 1960s. Up until 1970s, this new idea was only used by Russian researchers. In the seventies, a book by Itkis [5] and a survey paper by Utkin [6] made this method known worldwide.

Since then, Sliding Mode Controllers have been developed and successfully implemented in different applications such as nonlinear control, MIMO, discrete-time models, large scale and Infinite-Dimensional systems [7]. Some applications of SMC have been presented [8, 9]. By using discontinuous feedback control laws, SMC forces the system state to slide on a switching surface located between the bounds of the state space. The controller tries to keep the system in the specified surface. One of the advantages of using Sliding Mode Controller is that by movement on the sliding surface, the system becomes insensitive to some model uncertainties and perturbations. Therefore, the controller has acceptable performance even with these

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uncertainties [7]. On the other hand, Sliding mode controller has two main disadvantages. One is its dependency on the dynamic of the nonlinear part of the model and the other is the chattering phenomenon [10]. To eliminate these disadvantages, a fuzzy inference mechanism is used as the equivalent part of SMC. So, a fuzzy inference mechanism is used as the equivalent part of SMC to eliminate such disadvantages.

The term fuzzy logic was first introduced by Lotfi Zadeh in 1965 [11] and since then it has been used in numerous industrial applications such as in washing machines, elevators, trains, cranes, automotive industry, traffic control, and medical diagnosis [12]. Various combinations of fuzzy logic controller (FLC) with sliding mode controller (SMC) have been proposed in [13-15]. Fuzzy sliding mode controller (FSMC) takes the advantages of SMC like robustness, stability, and insensitivity against some uncertainties, and uses Fuzzy logic controller to eliminate disadvantages of SMC like nonlinear dynamic dependency [8-9]. Various combinations of fuzzy controller with sliding mode controller has been proposed in [11, 16-31]. The second disadvantage of SMC is the chattering problem; because the controller practically uses switching imperfections, there is not any ideal sliding mode controller. Discontinuity in the controller will lead to a dynamic behavior close to the sliding surface which is called chattering. This chatter can weaken the performance of the system. In mechanical systems, this chatter causes wear and tear in mechanical parts of the system [13]. In electrical systems, chatter causes a high-frequency control action. This high-frequency control action causes high heat losses in electrical power circuits [14]. The chattering phenomenon is illustrated below [15].

Although in practice there are no sliding mode controllers without chattering problem [16], various methods have been proposed to diminish it. In [17], Daly and Wang introduced a sliding mode controller with an equivalent output injection sliding mode observer. These authors in [17] presented a sliding mode controller with an observer. They proved that by using feedback available from the output of the system, this observer could estimate the unknown disturbances and diminish the chattering of the system. According to another research done by Haskara et al. [18], the discontinuous term of the sliding mode controller may be regarded as a mixture of a low frequency equivalent control and a high-frequency switching signal. By passing the signal to a low pass filter with appropriate bandwidth, the equivalent output injection term might be extracted [17]. J.J.E. Slotine in [19] proposed a sinusoidal function as a regulation scheme in the vicinity of the switching surface to remove the chattering. In some research saturation function has been used around the sliding surface to remove the chattering [20-21]. Although the fixed saturation function diminishes the chattering, it reduces the robustness of the sliding mode controller. Figure 2 illustrates the saturation function [15].

In this study, a novel variable boundary layer method is introduced which removes the chattering phenomenon as it keeps the controller robust.

In Table 1 the advantages and disadvantages of SMC, FSMC with sign function, FSMC with fixed saturation boundary layer, and FSMC with variable saturation boundary layer are proposed.

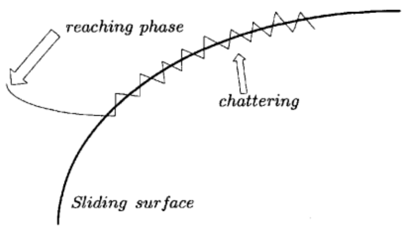

Figure 1. The chattering phenomenon caused by discontinue part of SMC

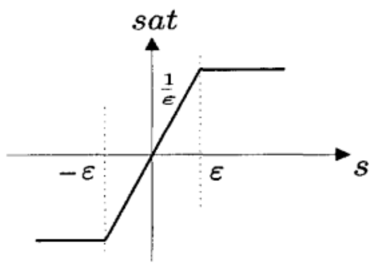

Figure 2. The saturation function with fixed boundary layers

TABLE 1. The advantages and disadvantages of FLC, SMC, and FSMC

Controller's name	Advantages	Disadvantages
SMC	insensitive to external disturbances stable	chattering phenomenon dynamic dependency
FSMC with sign function	insensitive to external disturbances stable Model-free	chattering phenomenon
FSMC with fixed saturation boundary layer	insensitive to external disturbances stable Model-free	reduces the robustness of controller Chattering diminished but not completely removed
FSMC with auto-adjustable saturation boundary layer	insensitive to external disturbances stable Model-free robust chatter-free	----

The rest of this paper has been organized as follows. In Section 2, the dynamic formulation of vehicle suspension system has been presented. Fuzzy sliding mode controller with auto-adjustable boundary layers has been presented in Section 3. In Section 4, simulation, results and discussions and finally in Section 5, the conclusion has been presented.

2. DYNAMIC FORMULATION OF VEHICLE SUSPENSION SYSTEM

It seems that the concept of designing a suspension system for a vehicle is both interesting and challenging. To simplify such challenging matter, in this paper one of the four wheels of the vehicle suspension system has been designed and used as the plant to test the performance of the proposed controller. The vehicle suspension system is illustrated in Figure 3.

The simplified suspension system which is a quarter of the whole suspension system of the vehicle models the tire by a spring and a damper which only receives vertical forces. The forces from the road that hit the tire are called road profile (Fr). In order to make the model simpler, the horizontal forces are ignored. The system also includes both the spring mass (M_1) and the unspring mass (M_2). The dynamic equations of the nonlinear passive vehicle suspension system are:

$$M_1\ddot{y}_1 = -b_1(\dot{y}_1 - \dot{y}_2) - k_1(y_1 - y_2) + F \quad (1)$$

$$M_2\ddot{y}_2 = -b_1(\dot{y}_1 - \dot{y}_2) + k_1(y_1 - y_2) + b_2(\dot{Fr} - \dot{y}_2) + k_2(Fr - y_2) - F \quad (2)$$

where $\boldsymbol{M_1}$ is the body mass, $\boldsymbol{M_2}$ the suspension mass, $\boldsymbol{k_1}$ the spring constant of suspension system, $\boldsymbol{k_2}$ the spring constant of wheel and tire, $\boldsymbol{b_1}$ the damping constant of suspension system, $\boldsymbol{b_2}$ the damping constant of wheel and tire, $\boldsymbol{F}$ the control force, and $\boldsymbol{Fr}$ the Road profile. The vehicle suspension model has the following parameters:

TABLE 2. The vehicle suspension model parameters

Symbol	Value	Description
m_1	2500(Kg)	Vehicle body mass
m_2	320(Kg)	Vehicle suspension mass
k_1	8000(N/m)	Suspension spring linearized stiffness
k_2	500000(N/m)	Wheel and tire spring linearized stiffness
b_1	350(N.s/m)	Suspension damping linearized stiffness
b_2	15020(N.s/m)	Wheel and tire damping linearized stiffness

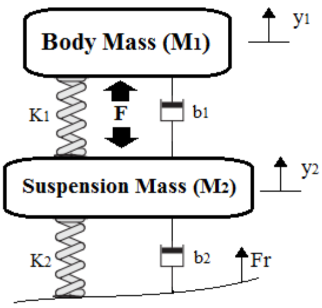

Figure 3. The vehicle suspension system

3. DESIGNING FUZZY SLIDING MODE CONTROLLER (FSMC) WITH AUTO-ADJUSTABLE BOUNDARY LAYERS

In this section fuzzy sliding mode controller with auto-adjustable boundary layers is designed to control the vehicle suspension system. The process of designing of the controller has been described in 4 steps. In step 1, the formulas of fuzzy sliding mode controller (FSMC) are presented. FSMC consists of two parts; in step 2, the discontinuous control part of SMC is described. In step 3, the equivalent-like fuzzy part of FSMC is described, and finally, in step 4, fuzzy inference mechanism is applied. This fuzzy mechanism tunes the boundaries of the saturation function of the FSMC on-line.

3.1. Fuzzy Sliding Mode Controller (FSMC) In order to design the controller, the dynamic equation of the system has been replicated as below [22]:

$$\dot{x}_p = f(x_p, Fr, t) + \Delta f(x_p, Fr, t) + K_c F \quad (3)$$

where $f(x_p, Fr, t)$ represents the nominal dynamic of the system, and $\Delta f(x_p, Fr, t)$ the nonlinearities and dynamics which are caused by changes of the dynamic variables, Fr is the road profile input, and F the control efforts. The tracking error is defined as:

$$e = y_{ref} - y \quad (4)$$

where $\boldsymbol{y_{ref}}$ the desired vertical position and $\boldsymbol{y}$ defined as:

$$y = y_1 - y_2 \quad (5)$$

The sliding surface is calculated as below:

$$S = G^T(\dot{e} + \lambda e) \quad (6)$$

where λ is the sliding surface gain which is strictly positive, and G^T a constant matrix. To force the system state to slide on the switching surface, we should have $\dot{S} = 0$ [22].

$$\dot{S} = G^T(\ddot{e} + \lambda \dot{e}) = 0 \quad (7)$$

A fuzzy controller has been used as the equivalent control force which is called $u_{eq_{fuzzy}}$. To satisfy the sliding condition ($\dot{S} = 0$), a discontinuous term u_{dis} is added to the equivalent control force.

$$u = u_{eq_{fuzzy}} + u_{dis} = u_{eq_{fuzzy}} + (G^T)^{-1}\nu \qquad (8)$$

$\boldsymbol{\nu}$ is calculated as:

$$\nu = -k_s.sgn(S) \qquad (9)$$

where k_s is the switching gain, and $sgn(.)$ represents the sign function. By substituting (11) in (10), the total control force is calculated as below:

$$u = u_{eq_{fuzzy}} + (G^T)^{-1}[-k_s.sgn(S)] \qquad (10)$$

To eliminate the chattering problem, the sign function is replaced with an auto-adjustable saturation function. The total control force now becomes:

$$u = u_{eq_{fuzzy}} + (G^T)^{-1}[-k_s.sat\left(\frac{S}{\varepsilon}\right)] \qquad (11)$$

where $\boldsymbol{\varepsilon}$ is a positive constant which is tuned online with a fuzzy inference mechanism, and sat (.) is defined as below.

$$sat\left(\frac{S}{\varepsilon}\right) = \begin{cases} \frac{S}{\varepsilon} \; for \; \left|\frac{S}{\varepsilon}\right| \le 1 \\ 1 \; for \; \left|\frac{S}{\varepsilon}\right| \ge 1 \end{cases} \qquad (12)$$

3. 2. Equivalent-Like Fuzzy Part of FSMC In this section, the equivalent-like fuzzy logic controller (FLC) used in the controller has been applied. The FLC that has been applied is based on Mamdani's method. Figure 4 illustrates the structure of the equivalent-like fuzzy controller [12].

3. 2. 1. Fuzzification. First, the inputs and the outputs of the equivalent-like fuzzy controller must be determined. Here, the controller has two inputs $(e, \dot{e})$ and one output (U_f). The input e is the error which measures the difference between desired and actual input. The input "$\dot{e}$" indicates the change of the error. Second, appropriate membership functions (MFs) must be selected. By using different MFs, it has been concluded that triangular MF shape has the best output response in this work. The membership function of the two inputs and one output of the fuzzy controller are shown in Figure 5. In Figure 5, the fuzzy subset of inputs and output linguistic variables are expressed as Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), and Positive Big (PB).

3. 2. 2. Fuzzy Rule Base. In fuzzy rule base each rule is made of two parts. The first part is called antecedent which consists of an inequality or an inference. The second part is called consequent which concludes and is the output if the antecedent is satisfied. An example is shown below [23]:

$FR: If\ A, then\ B$

where A is the antecedent and B is the consequent. The fuzzy rule base used here is composed of 49(7x7) rules which are shown in Table 3. Two fuzzy rules used in this controller are [23]:

$FR^1: If\ e\ is\ NB\ and\ \dot{e}\ is\ NB, then\ U_f\ is\ NB$
$FR^2: If\ e\ is\ PB\ and\ \dot{e}\ is\ NB, then\ U_f\ is\ ZE$

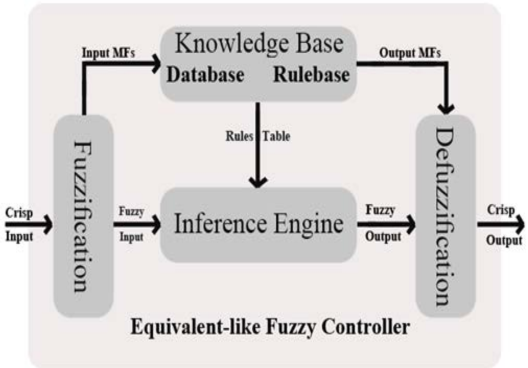

Figure 4. The structure of the equivalent-like fuzzy controller [12]

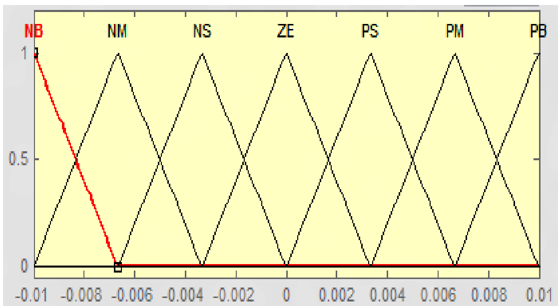

Figure 5. The membership functions of inputs and output of equivalent-like fuzzy controller

TABLE 3. The fuzzy rule base

		Change of error ($\dot{e}$)						
		NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
Error (e)	**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

3. 2. 3. Aggregation of the Rule Outputs. The act of finding overall conclusion from consequents made by each rule is called aggregation. Max-Min aggregation method is used in this research. The calculation of this method is described bellow.

$$\mu_U(x_k, y_k, u) = \max\left\{min_{i=1}^{r}\left[\mu_{R_{pq}}(x_k, y_k), \mu_{FR}(x, y, u)\right]\right\} \quad (13)$$

where x_k, y_k are the input rules, r is the number of activated rules, and $\mu_{R_{pq}}(x_k, y_k)$ are fuzzy equivalents of the antecedent parts of the activated rule [24].

3. 2. 4. Defuzzification. The process which changes fuzzy output set to crisp output value is called defuzzification. So far, various types of defuzzifications have been introduced. The center of area (COA) principle is used in this paper. In COA principle, the crisp output is calculated as below:

$$\mu_{FC}(x_k, y_k) = \frac{\sum_i u_i \mu_u(x_k, y_k, u_i)}{\sum_i \mu_u(x_k, y_k, u_i)} \quad (14)$$

where $\mu_u(x_k, y_k, u_i)$ is the membership function, $\mu_{FC}(x_k, y_k)$ the crisp output value, and u_i an element of the output fuzzy set [24]. Figure 6 illustrates the Simulink block diagram of the equivalent-like fuzzy controller in Simulink.

3.3. Fuzzy Inference Mechanism for Auto-adjustable Boundary Layers A fuzzy inference mechanism is applied to the controller to tune the values of upper and lower boundaries of the saturation function on-line. Figure 7 illustrates the structure of the applied auto-adjustable saturation boundary layers method. The fuzzy inference mechanism used in this work has the following structure; the fuzzy inference mechanism has one input and two outputs. The error is used as the input; upper boundary limit and lower boundary limits are used as the outputs. The membership functions of the input and the outputs are illustrated in Figure 8.

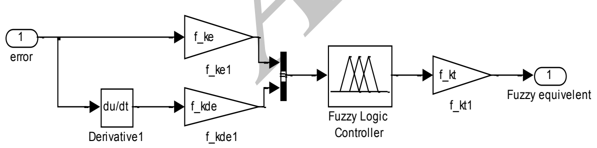

Figure 6. The block diagram of the equivalent-like fuzzy controller

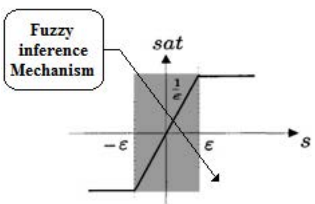

Figure 7. The saturation function of the sliding mode controller with auto-adjustable boundary layer

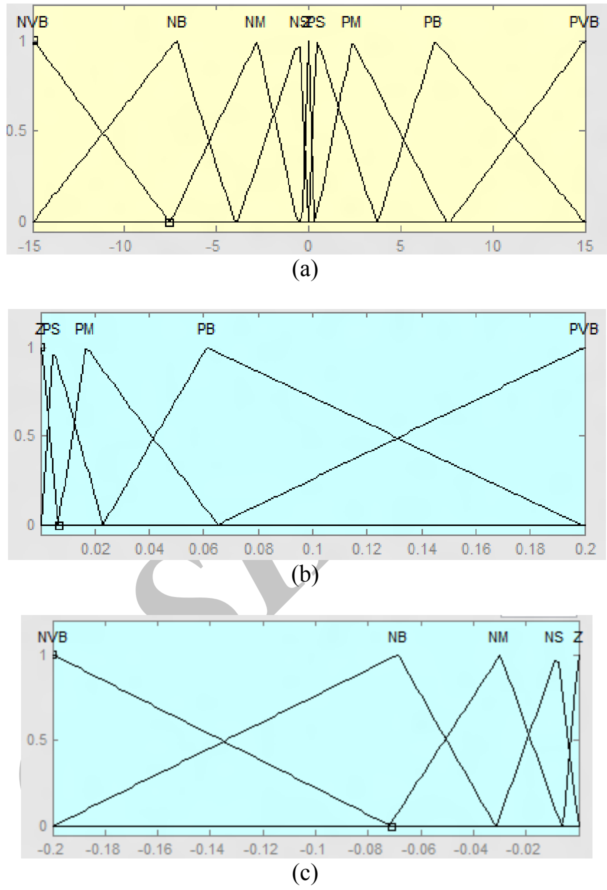

Figure 8. a) The membership functions of the error (input), b) The membership functions of the upper boundary limit (output 1), and c) The membership functions of the lower boundary limit (output 2)

TABLE 4. The fuzzy inference mechanism rule base

Error	NVB	NB	NM	NS	Z	PS	PM	PB	PVB
Upper Boundary	PVB	PB	PM	PS	Z	PS	PM	PB	PVB
Lower Boundary	NVB	NB	NM	NS	Z	NS	NM	NB	NVB

In Figure 8, N is negative, P positive, V very, B big, M medium, S small, and Z zero. The applied fuzzy inference mechanism has only 9 rules. This makes the implementation of the proposed method both easy and computationally efficient. The fuzzy rules are shown in Table 1. The fuzzy inference mechanism is designed in such a way that removes the chattering of the fuzzy sliding mode controller. The fuzzy inference mechanism carries out this process by changing the upper and lower boundaries of the saturation function on-line. The block diagram of the fuzzy sliding mode controller with auto-adjustable boundary layers is illustrated in Figure 9.

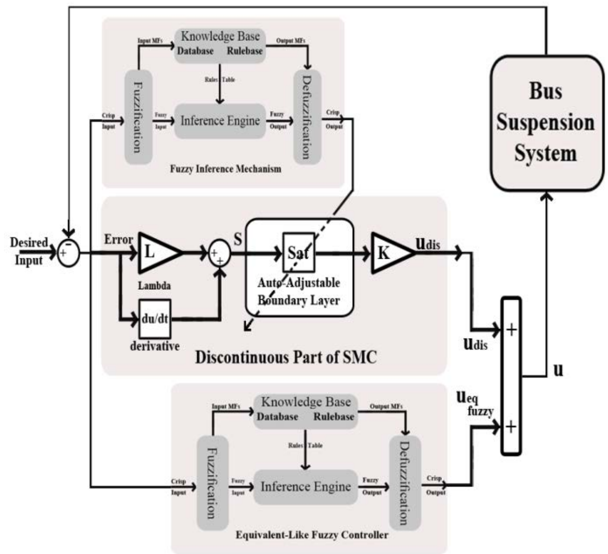

Figure 9. Block diagram of the fuzzy sliding mode controller with auto-adjustable boundary layers implemented on the vehicle suspension system

4. RESULTS AND DISCUSSIONS

In this section, 3 steps have been taken into account to illustrate the results. First, three controllers, FSMC with sign function, FSMC with fixed saturation boundary, and FSMC with auto-adjusting saturation boundary layers have been implemented in the vehicle suspension system. Second, two simulations have been done. In the first simulation, a step function has been used as the road profile to represent a vehicle coming out of a pothole. In the second one, a sinusoidal wave has been used as the road profile to simulate the vehicle moving on a bumpy road. Finally, Track following performances, error performances, Integral absolute errors, and control efforts of the controllers are calculated and compared with each other.

4. 1. Simulation 1. The Vehicle Coming out of a Pothole Figures 10-11 and Table 5 present the results of the track following of the controllers. From Figure 10, it is concluded that FSMC with auto-adjustable saturation boundary layers has better settling time and has lower overshoot. In Figure 11, the results are shown in a magnified scale of [-0.05 0.05] where the x-axis represents the time and Y-axis represents the track following performance of the controller. It is obvious that FSMC with sign function has intensive chattering. FSMC with fixed saturation boundary layers has diminished the chattering, but we can see that it has also decreased the robustness of the system. It is noticeable that FSMC with auto-adjustable saturation boundary layers has almost removed the chattering, whereas it maintains more robustness compared with the other controllers. Figure 12 illustrates the error performance for the vehicle suspension system. It is observed that FSMC with auto-adjustable saturation boundary layer has better error performance compared to other controllers. Integral Absolute Errors of the controllers are calculated and illustrated in Figure 13. The applied method has effectively reduced the integral absolute error of the conventional fuzzy sliding mode controller with fixed saturation boundaries.

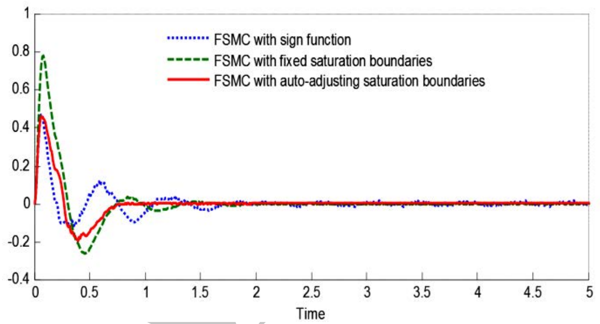

Figure 10. The vertical displacement of the vehicle suspension system for FSMC with sign function, FSMC with fixed saturation boundary, and FSMC with auto-adjusting saturation boundary layer

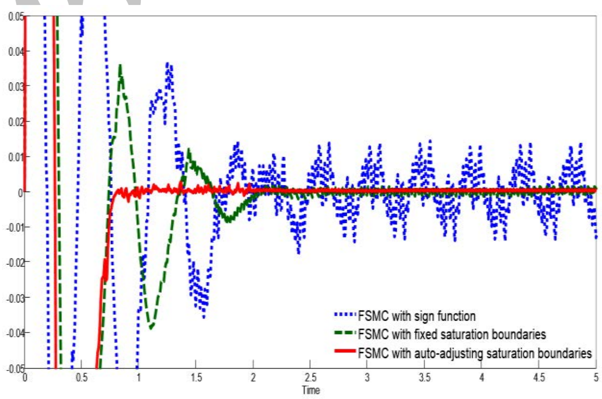

Figure 11. The magnified Vertical displacement of the suspension system for the controllers.

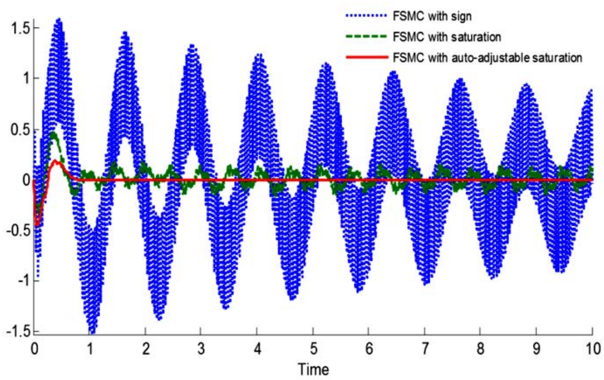

Figure 12. Error performance of the controllers on the vehicle suspension model

TABLE 5. Track following data the controllers

Method	Settling time (s)	Over shoot	Chattering boundary (%)
FSMC with sign function	--	0.12	0.013
FSMC with fixed saturation boundary	1.8	0.26	0.0013
FSMC with auto-adjustable saturation boundary layer	0.8	0.195	0.0001

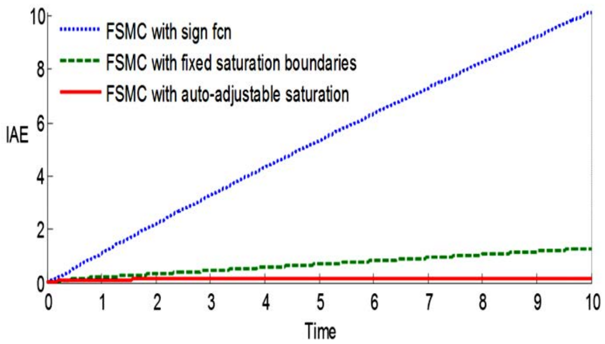

Figure 13. IAE of the controllers implemented on vehicle suspension system

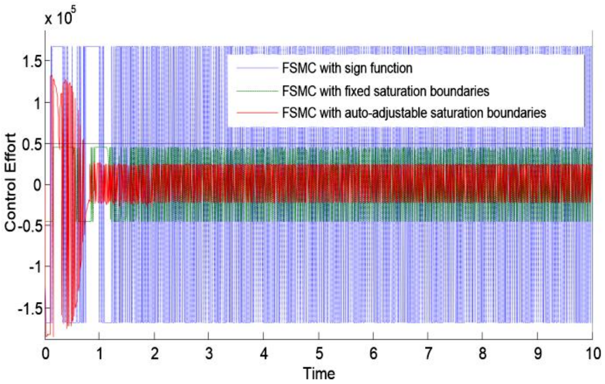

Figure 14. The control force provided by the suspension actuator.

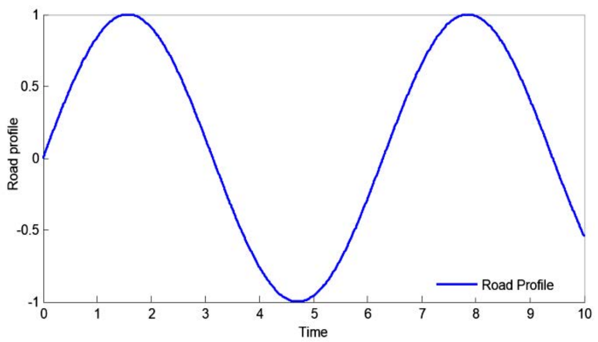

Figure 15. The sinusoidal wave, representing a bumpy road

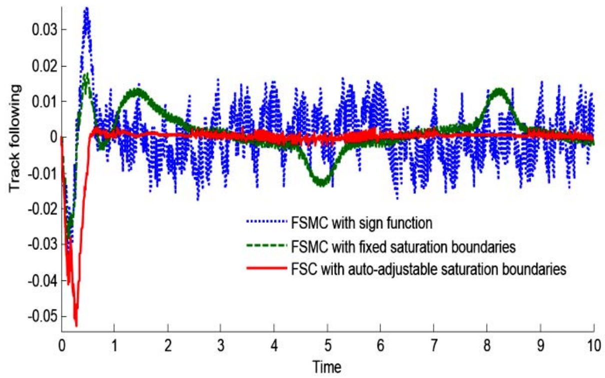

Figure 16. Track following of the controllers for the vehicle suspension system on a bumpy road

Figure 14 illustrates the control efforts. It is concluded that the proposed method uses the least control effort while FSMC with sign function uses the most. From the Simulation results of the respond of the vehicle suspension of moving out of a pothole, it is confirmed that the FSMC with auto-adjustable saturation boundaries has much better performance compared with other controllers.

4. 2. Simulation 2 . The Vehicle on a Bumpy Road

A sinusoidal wave has been used as the road profile to simulate a bumpy road. Figure 15 illustrates this road profile. The tracking performance of the vehicle on a bumpy road is illustrated in Figure 16. After a short period of time, roughly 0.5 s, the proposed method follows the trajectory. The FSMC with fixed saturation boundaries can roughly follow the track, while the FSMC with sign function has huge chattering. The proposed controller has diminished the chattering of the system and has much better performance compared with the other controllers. The error performances of the controllers are shown in Figure 17. As Figure 17 reveals, after roughly 0.5 s, the proposed method has decreased the error to zero. The other controllers decrease the error but they cannot remove it completely. Integral absolute errors (IAEs) of the controllers are compared in Figure 18. After 10 s, the proposed controller has only 0.03 IAE while FSMC with fixed saturation boundaries has 0.06 IAE and FSMC with sign function has 0.15 IAE. Figure 19 illustrates the control efforts of the controllers. The control effort of the proposed method is about 0.02×10^5. The control effort of FSMC with fixed saturation boundaries is about 0.5×10^5 and the control effort of FSMC with sign function is about 1.8×10^5. The proposed method has the least control effort compared with other controllers. From the simulation results for the bumpy road and pothole, it is concluded that the FSMC with auto-adjustable saturation boundaries has superbly better performance compared with the other controllers.

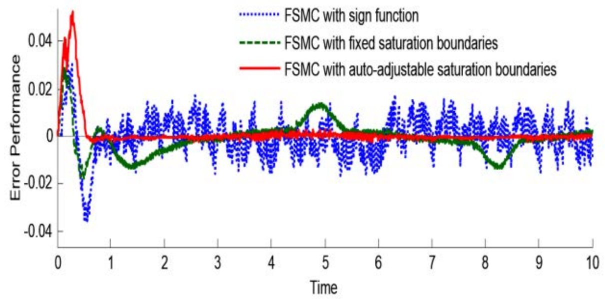

Figure 17. Error performance of the controllers for the vehicle suspension system on a bumpy road

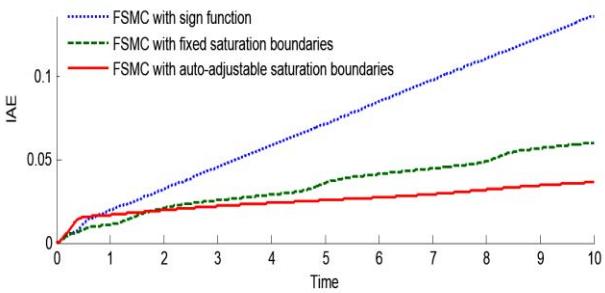

Figure 18. Integral absolute errors of the controllers for the vehicle suspension system on a bumpy road

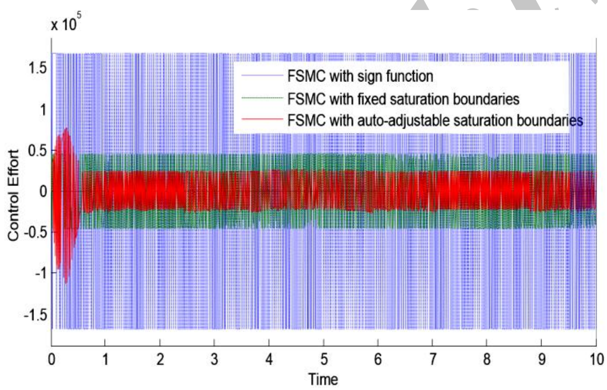

Figure 19. Control efforts for the vehicle suspension system on a bumpy road

5. CONCLUSION

In this paper, a new fuzzy sliding mode controller with auto-adjustable saturation boundary layers has been proposed. The main idea is to tune the boundary layers of the controller on-line in order to diminish the chattering of the controller, while maintaining the robustness of the controller. A new fuzzy inference mechanism was used to tune the boundary layers of saturation function on-line. Then, the proposed controller was compared with two controllers, a FSMC with sign function and a FSMC with fixed saturation boundary layers. To evaluate the performance of the controllers, they were implemented in a vehicle suspension system. The results of the simulations indicate that the presented method has better tracking performance and lower error compared with the other controllers. It can also be verified that the proposed method has efficiently diminished the chattering phenomenon. Furthermore, the results prove that the proposed method has better robustness compared with the other controllers.

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A New Fuzzy Sliding Mode Controller with Auto-adjustable Saturation Boundary Layers Implemented on Vehicle Suspension

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چکیده

این مطالعه توسعه‌ی کنترل حالت کشویی (لغزشی) فازی (FSMC) بر اساس لایه‌ی مرزی متغیر است. برای تنظیم ضخامت لایه‌ی مرزی به منظور کنترل درجا (روی خط) از مکانیزم استنتاج فازی استفاده شده است. برای کاهش آهنگ محاسبه‌ی کنترل، از یک قانون کمینه استفاده شده است. هدف از این مقاله طراحی یک کنترلر با توانایی حذف لرزش و حفظ استحکام کنترل به طور همزمان است. برای اثبات اثربخشی این روش، شبیه سازی با استفاده از نرم افزار MATLAB / SIMULINK انجام شده است. در این شبیه سازی، نتایج حاصل از 3 کنترل، FSMC با لایه‌ی مرزی خودتنظیم کننده، با لایه‌های مرزی ثابت و FSMCهای با تابع علامت FSMC مقایسه شده‌اند. نتایج حاصل از شبیه سازی نشان داده است که عملکرد حالت کشویی کنترل کننده‌ی فازی بر اساس روش لایه‌ی مرزی خودتنظیم کننده نسبت به روش لایه‌ی مرزی ثابت برتری دارد.

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