Grzegorz Ślaski
Poznan University of Technology, Institute of Machines and Motor Vehicles

Michał Maciejewski
Poznan University of Technology, Institute of Machines and Motor Vehicles

DESIGN OF A FUZZY LOGIC CONTROLLER FOR A SEMI-ACTIVE VEHICLE SUSPENSION

Abstract: This paper presents the application of fuzzy logic to control semi-active suspension. Investigations were made with a use of a non-linear quarter car suspension model with characteristics of a real semi-active shock absorber with a bypass valve. The other parameters of the model were estimated on a vehicle equipped with this type of shock absorbers and reduced to a quarter car model parameters. Authors compared a performance of three models: a passive model, a skyhook strategy controlled model, and a fuzzy logic skyhook based controlled model. The results showed that fuzzy control gives a potential for improvement of suspension operation and much greater opportunities of control strategy construction in a comparison to the classical two state skyhook control strategy.
Keywords: quarter car model, semi-active suspension control, fuzzy logic controller

1. INTRODUCTION

The aim of a vehicle suspension is to provide an isolation of a vehicle body from road irregularities and to ensure good road holding. The first goal lies within the area of ride analysis and concerns a problem of how to reduce a discomfort experienced by vehicle occupants. The second one lies within the area of handling analysis. Here, the handling means an ability of a vehicle to safely accelerate, brake and corner with the "ease-of-use".

The design goal is to minimize both the acceleration of the body and the dynamic tire load, while operating within the constraints of suspension rattle space for a given suspension parameter set.

One way to improve the ride quality and the safety level is to adjust suspension parameters to a weight of car and its load, and also to a type of road excitation. There are two elements of a suspension having influence on its performance – a spring element and a damper. In case of a passive suspension a designer has to assume the most frequent conditions of driving and find the best suspension stiffness and damping for these conditions. In general, it is the problem of suspension optimization.

Using spring elements of a variable stiffness and damping elements of a variable damping ratio, a suspension is able to adapt to various driving conditions.

As in case of a passive suspension the designer has to find an optimal parameter set for the spring and the damper to reach the trade-off between comfort and safety, in case of a suspension with variable stiffness and damping he can define an area of a compromise (not just single values for both stiffness and damping). Having the variable-parameter suspension the main problem lies in finding of a real-time control algorithm for these parameters. There are some known control strategies such as on-off skyhook, on-off groundhook, continuous skyhook, hybrid control strategy and many others.

This article presents an application of fuzzy logic control theory to building of a controller for semi-active suspension. The presented suspension is a precise model of a real passenger vehicle (compact class front wheel drive car with estate body) rear suspension and real shock absorber with a continuously changeable damping coefficient.

2. SUSPENSION MODEL

A linear quarter car model is a model of a car suspension that is most often used for a preliminary design of a suspension and semi-active suspension controllers. This model is adequate only for investigation of the bounce motion of the chassis and the wheel without taking into account pitch and roll vibration.

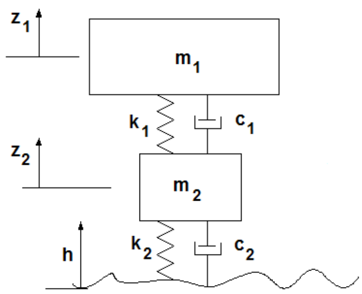


Fig. 1. Quarter car passive suspension model

However, in this paper a more complicated quarter car model was used to investigate a behavior of a suspension of a chosen type of a car with electronically controlled shock absorbers. The model has nonlinear characteristics of spring and shock absorber determined by experimental tests conducted on a real suspension and suspension elements. These test were described in the earlier papers [1,2]. The model was implemented in Matlab/Simulink environment and was described by a pair of second-order differential equations of motion:

$$\ddot{z}_1 = {}^{1}/_{m_1} \cdot (F_{k1} + F_{c1}) - g$$

$$\ddot{z}_2 = {}^{1}/_{m_2} \cdot [(F_{k2} + F_{c2}) - (F_{k1} + F_{c1})] - g$$

where:
$\ddot{z}_1$ - vertical acceleration of the sprung mass,
$\ddot{z}_2$ - vertical acceleration of the unsprung mass,
F_{k1}, F_{k2} – stiffness forces of the suspension spring and the tire:

$$F_{k1} = k_1(z_2 - z_1), \qquad F_{k2} = k_2(h - z_2)$$

F_{c1}, F_{c2} – damping forces of the shock absorber and the tire:

$$F_{c1} = c_1(\dot{z}_2 - \dot{z}_1), \qquad F_{c2} = c_2(\dot{h} - \dot{z}_2)$$

g - acceleration due to Earth's gravity; equal to 9,81 m/s^2

Suspension stiffness and suspension damping coefficients are not a constants like in a linear model. The suspension stiffness coefficient is a function of suspension deflection, and damping coefficient is a function of suspension velocity and control signal level (controller use 0 for minimum value and 1 for maximum value and this is calculated to the shock absorber valve current in amps).

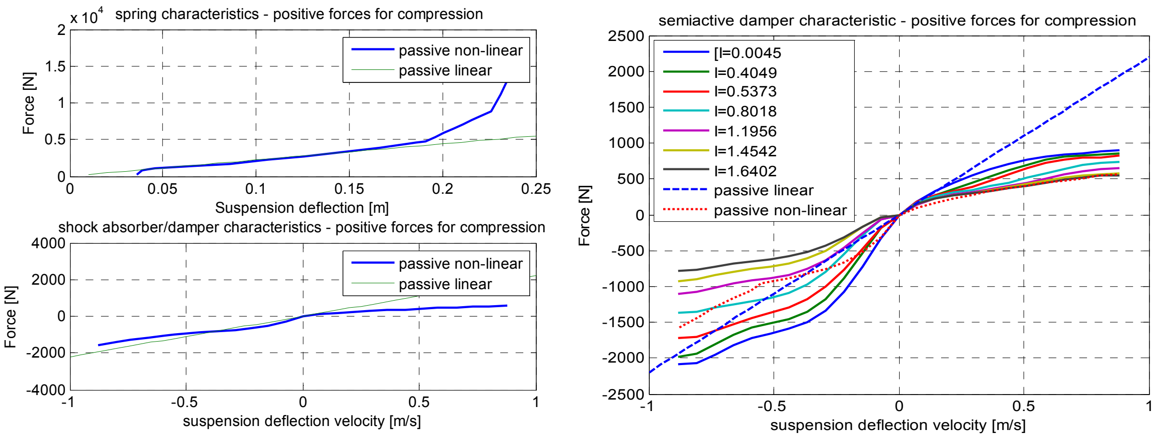


Fig. 2. Characteristics of nonlinear quarter car suspension model

Suspension model was implemented in Simulink and was built using blocks – each block for each functional element of the suspension model: body mass, spring and damper, wheel, tire and controller and also subsystem for calculation of longitudinal dynamics and road excitations (Fig. 3).

3. SUSPENSION CONTROLLER

Authors investigated two controllers for the presented nonlinear quarter car suspension model. A classical skyhook strategy controller and a fuzzy logic controller which is a generalization of the former one. The results obtained for both controllers were compared to the results for passive nonlinear suspension. The model of suspension is based on rear suspension of real passenger car of compact class with by-pass valve type semi-active shock absorbers.

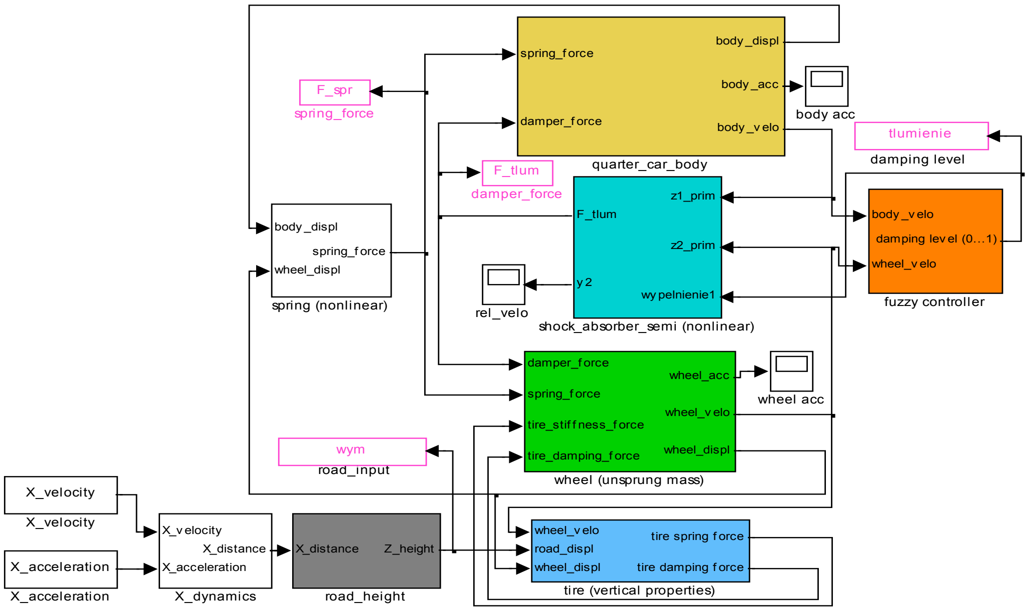


Fig. 3. Structure of nonlinear semi-active quarter car suspension model with a fuzzy logic controller

3.1. Skyhook controller

The most known and simplest skyhook control strategy is called an on-off skyhook. Using this strategy the damper is controlled by switching between two damping values – minimum and maximum. Determination of whether the damper is to be adjusted to high- or low-damping state depends on the product of the suspension velocity (relative velocity of the body against the wheel) and the absolute velocity of the vehicle body. If the product is positive or zero, the damper is adjusted to its high state, otherwise, the damper is set to the low state. For the quarter-car model (Fig. 1), this strategy is summarized by:

$$\dot{z}_1 \cdot \dot{z}_{12} \geq 0 \Rightarrow maximum\ damping$$
$$\dot{z}_1 \cdot \dot{z}_{12} < 0 \Rightarrow minimum\ damping$$

When the damper is in a rebound phase, the force of the damper acts to pull down on the vehicle body mass; when the damper is in a compression phase, the force of the damper pushes up on the mass. Thus, when the absolute velocity of the body mass is negative and it is traveling downwards the maximum (high state) value of damping is desired to push up the mass. If the absolute velocity of the body mass is positive – the mass is traveling upwards, the maximum (high state) value of damping is desired to pull down the mass. The on-off skyhook semi-active policy emulates the ideal body displacement control configuration of a passive damper “hooked” between the body mass and the “sky”.

3.2. Fuzzy logic controller

Fuzzy logic is a form of a multi-valued logic as opposed to a classical two-valued logic. It was based on fuzzy set theory by Lotfi Zadeh [4,5] and proposed to deal with impreciseness. Fuzzy logic, although being still controversial for some mathematicians, has gained a great popularity and appreciation, and has been successfully applied in many scientific areas.

One of these areas is control theory where fuzzy logic is often applied to dynamic process control in a form of a fuzzy controller. Fuzzy controllers are widely used in the automotive industry where automatic transmissions, ABS and cruise control systems are frequently based on this paradigm of control theory.

The idea of fuzzy control is to operate on rules that are human-readable and represent a human's heuristic knowledge about how to control a process. All rules are represented in a form of fuzzy logic implications. A fuzzy controller consists of four main components presented in Fig.4

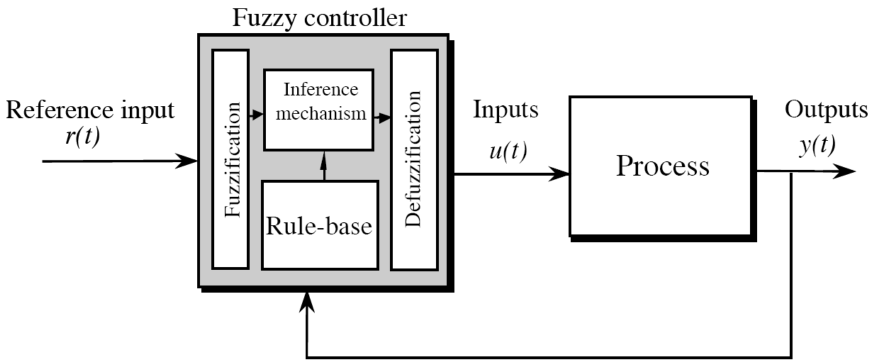


Fig.4. Fuzzy controller architecture [6]

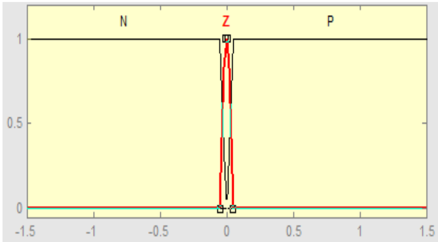
Fuzzy control has many properties that make it suitable for semi-active suspension control. First of all, a semi-active suspension is a complicated nonlinear system. It consists of many elements that has nonlinear dynamics, e.g. tires, shock absorbers, springs and some rubber elements. Of course all these nonlinearities may be linearized with a lesser or greater impact on the model precision.

Secondly, and even more importantly, there exists no single optimal control criteria for semi-active suspension policy. In general, it is assumed that vehicle suspension operation should be considered with two criteria: safety and comfort. These two criteria are generally conflicting with each other, but neither of them can be described with a single commonly accepted and optimality proven measure. As a result, scientists and engineers use different arbitrary chosen heuristic measures.

As it was stated in the previous sections, a fuzzy controller can be easily provided with different heuristic rules that directly or indirectly aim in maximization or minimization of any selected measures. In the conducted research the fuzzy controller was implemented as an extended version of classical skyhook control policy in Matlab/Simulink environment and with the use of Fuzzy Logic Toolbox [7].

Similarly to the classical skyhook controller, the input for the fuzzy controller were the sprung mass absolute velocity and the suspension velocity (velocity difference between the sprung mass (body) and the unsprung mass (wheel)). Input signals were fuzzified according to the set of trapezoid membership functions presented in Fig.5a with three linguistic variables: N – negative, Z – zero, and P – positive.

On the other hand, the controller output was the damping level (between 0 for minimum value and 1 for maximum value) of the semi-active damper. Fig. 5b presents the set of membership functions used for defuzzification of the output. The linguistic variables for the output were: S – small, M – medium, and L – large.

a) 

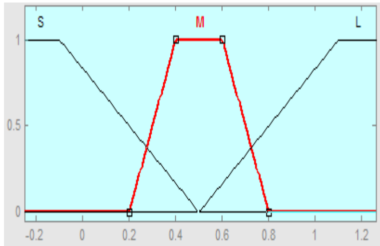
b) 

Fig.5. Membership functions: a) input signals (both input velocities), b) output signal (damping level)

The rules for the fuzzy controller were derived from the skyhook policy with the extension for Z (zero) variables. Fig.6 shows the set of rules in tabular and IF-THEN forms.

		v_{12}		
		N	**Z**	**P**
v_1	**N**	L	M	S
	Z	M	S	M
	P	S	M	L

```
IF (v1 is N) AND (v12 is N) THEN (c is L)
IF (v1 is N) AND (v12 is Z) THEN (c is M)
IF (v1 is N) AND (v12 is P) THEN (c is S)
IF (v1 is Z) AND (v12 is N) THEN (c is M)
IF (v1 is Z) AND (v12 is Z) THEN (c is S)
IF (v1 is Z) AND (v12 is P) THEN (c is M)
IF (v1 is P) AND (v12 is N) THEN (c is S)
IF (v1 is P) AND (v12 is Z) THEN (c is M)
IF (v1 is P) AND (v12 is P) THEN (c is L)
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Fig.6. Fuzzy logic rules

4. SIMULATION RESULTS

The simulation tests were conducted for three suspension models: nonlinear model of passive suspension, semi-active suspension with skyhook controller (SH), and semi-active suspension with fuzzy logic skyhook based controller (FL SH). The first case of road excitation was sinusoidal with changing frequency as it was assumed that the vehicle was braking from 20 m/s until stopped. Other road excitations consisted of two step inputs (plus 0.04 m and minus 0.04 m), one after another in specified distance, in order to simulate a pot hole and a bump in a kind of so-called “sleeping policeman”.

The absolute body displacement was lowered using both skyhook and fuzzy logic controllers – especially in the lower frequencies. Skyhook gave slightly better results. They were not as good as in the investigated earlier by the authors linear models [3] due to the real limitations of the modeled semi-active shock absorber. The minimum damping forces for the semi-active shock absorber for a compression phase were almost the same as for the passive shock absorber.

This fact has a good implication for safety measured as the tire deflection and the wheel displacement. This is a very important because of the limited suspension working space and the vertical tire load variations.

The skyhook strategy, the best for the body displacement optimization, gave the greatest wheel displacements. The fuzzy logic skyhook based strategy gave wheel displacements comparable with the passive suspension displacements at frequencies from 10 to 5 Hz, and only greater at smaller frequencies.

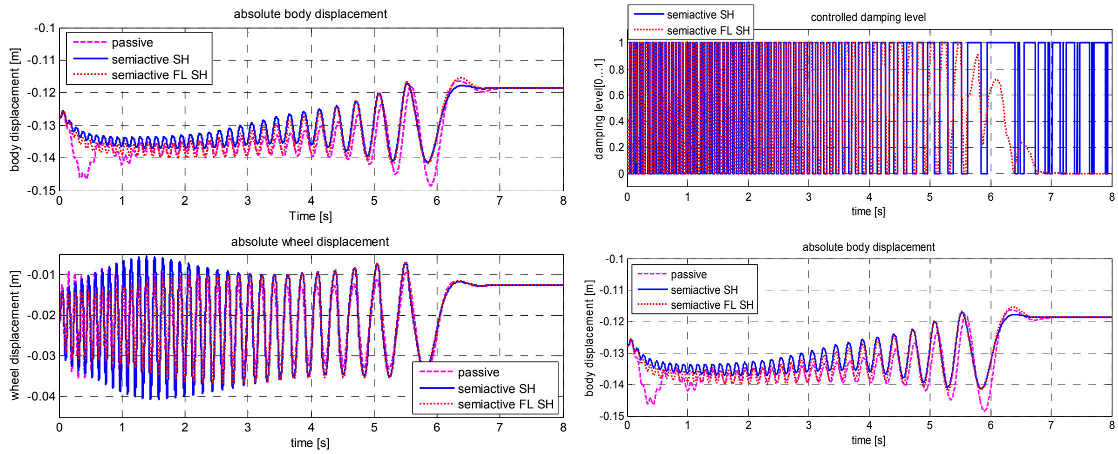

Fig.7. Simulation results for sinusoidal road input (wave length 2m, amplitude 0.01 m)

The response of the semi-active suspension on excitation in form of pot hole (depth: 0.04 m, length 0.1 m) was clearly more efficient than the response of the passive suspension what is shown in Fig. 8. Body displacement of both suspensions – with skyhook and fuzzy logic controllers were several times smaller than passive. Fuzzy logic controller gave slightly bigger body displacement but also smaller wheel displacement.

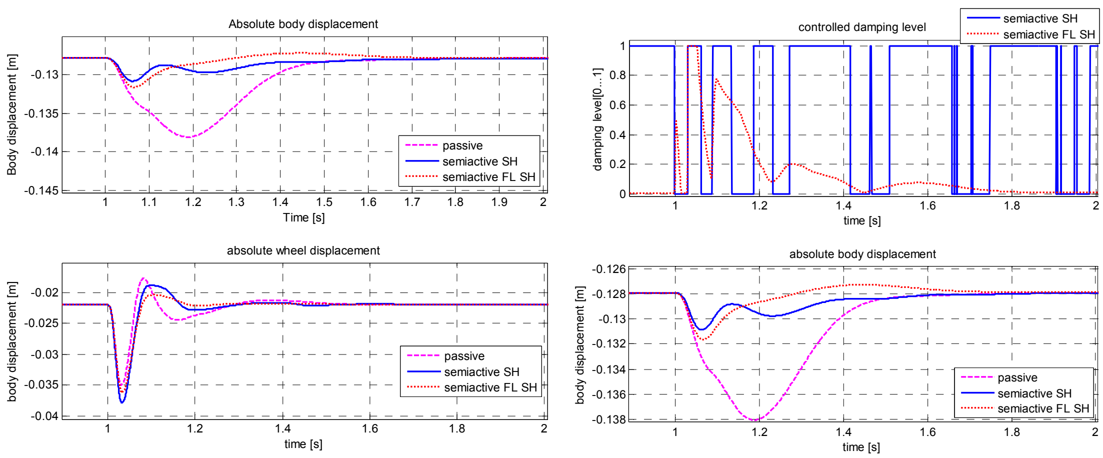

Fig.8. Simulation results for pot hole road input (depth 0.04, length 0.1 m)

Comparing damping levels of the skyhook and the fuzzy logic controller, we can see that in fact fuzzy logic controller gave continuously changeable damping levels.

5. CONCLUSIONS

In this paper, the example of the fuzzy logic control method applied to semi-active suspension was presented. Investigations made by authors showed that this method provides better compromise between the body and the wheel displacements and gives much more elastic construction of the control strategy than the classical on-off skyhook control strategy.

The presented examples outlined also the future research areas, i.e. the problem of optimization of the fuzzy logic rules and the membership functions. In the conducted research the fuzzy controller was tuned manually, but due to the large search space, finding the optimal configuration of the controller requires an automatic optimization procedure.

It should be pointed out that not only the controller but also the shock absorber characteristics (and its constraints) strongly influences the quality of the results. The investigated shock absorbers had a great potential for improving safety and comfort with higher vehicle loads but were not enough effective in improvement of comfort for sinusoidal road excitation. This was caused by a quite high level of the lower constraint for of the damping forces.

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PROJEKT STEROWNIKA LOGIKI ROZMYTEJ DLA ZAWIESZENIA PÓĞAKTYWNEGO SAMOCHODU

Streszczenie: W artykule przedstawiono przykład wykorzystania logiki rozmytej do sterowania zawieszeniem półaktywnym samochodu. Badania wykonano z wykorzystaniem nieliniowego modelu zawieszenia ćwiartki samochodu z charakterystyką rzeczywistego amortyzatora półaktywnego z zaworem obejściowym. Pozostałe parametry modelu były wyznaczone dla samochodu wyposażonego w ten typ amortyzatorów i zredukowane do parametrów modelu zawieszenia ćwiartki samochodu. Autorzy porównali jakość pracy zawieszeń pasywnego, sterowanego według zasady skyhook oraz sterowanego z użyciem sterownika rozmytego bazującego na zasadzie skyhook. Badania wykonane przez autorów pokazały, że ta metoda daje potencjał do poprawy działania zawieszenia oraz znacznie bardziej szerokie możliwości kształtowania strategii sterowania w porównaniu z klasyczną dwustanową strategią skyhook

Słowa kluczowe: ćwiartkowy model zawieszenia, zawieszenie półaktywne, sterownik logiki rozmytej