FUZZY CONTROL OF ANTI-LOCK BRAKING SYSTEM AND ACTIVE SUSPENSION IN A VEHICLE

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Résumé

Le but de ce travail est de proposer des contrôleurs robustes basés sur la logique floue pour un système de freinage antiblocage (ABS) couplé à une suspension active. Les principales difficultés de conception de contrôleur dans les systèmes automobiles sont liées à des non-linéarités élevées, des incertitudes causées par des perturbations externes et les variations des paramètres qui sont inconnus. L'objectif d'un système de contrôle d'ABS classique consiste à éliminer rapidement l'erreur de suivi entre le taux de glissement réel et une valeur de référence afin d'amener le véhicule à un arrêt dans le temps le plus court possible. Cependant, le temps de freinage et la distance d'arrêt peuvent être réduits encore davantage si le même système de contrôle considère également l'état du système de suspension active simultanément.

Un modèle de quart de véhicule à deux degrés de liberté est développé ainsi que des modèles pour une suspension active hydraulique et un système ABS. Le contrôleur a été développé en utilisant la théorie de contrôle flou et a été mis en œuvre sous l'environnement logiciel Matlab/Simulink.

Les résultats de simulation montrent que, pour un véhicule en particulier, il existe une application optimale de la force de suspension. Comparé à un système ABS non combiné avec la suspension active, le système de contrôle proposé peut améliorer les performances de freinage de manière significative.

Mots clés *: Suspension active, système d'anti-blocage, distance de freinage, contrôle à logique floue*.

Abstract

The aim of this paper is to propose robust controllers based on fuzzy logic for an Antilock Brake System (ABS) coupled with an active suspension. The main difficulties of controller design in automotive systems are related to high non-linearities, uncertainties caused by external perturbations and parameter variations which are unknown. The objective of a conventional ABS control system is to rapidly eliminate tracking error between the actual slip ratio and a set reference value in order to bring the vehicle to a stop in the shortest time possible. However, braking time and stopping distance can be reduced even further if the same control system also simultaneously considers the state of the active suspension system.

A two degree of freedom quarter car vehicle model is developed along with models for a hydraulic active suspension and an ABS system. The controller was designed by using the fuzzy model control theory and was implemented under the Matlab/Simulink software environment.

The simulation results show that for a particular vehicle there exists an optimal application of the suspension force. Compared with an ABS system without combing active suspension, the proposed control scheme can improve braking performance significantly.

Key words*: Active Suspension, Anti-Lock Brake, Braking Distance, fuzzy Logic Control*.

ملخص

الهدف من هذا العمل هو اقتراح تحكم قوي(etsuboR) على أساس المنطق الضبابي (euqigoL euolf) لنظام الفرامل المانعة للانغلاق (SBA) بالإضافة إلى نظام التعليق النشط. ترتبط الصعوبات الرئيسية من تصميم وحدة تحكم في أنظمة السيارات إلى ارتفاع اللاخطية، والإرتيابات الناجمة عن الاضطرابات الخارجية والاختلافات في العوامل الغير معروفة. دور نظام التحكم (SBA) التقليدي هو القضاء بسرعة على تتبع الخطأ بين نسبة الانزلاق الفعلية والقيمة المرجعية المنصوص عليها في النظام لجلب السيارة إلى التوقف في أقصر وقت ممكن. ومع ذلك، يمكن تخفيض وقت الكبح ومسافة التوقف أبعد من ذلك إذا كان نظام التحكم يعتبر في الوقت نفسه حالة نظام التعليق النشط.

تم تطوير نموذج ربع سيارة له درجتين من الحرية، إلى جانب نماذج لتعليق نشط الهيدروليكي ونظام (SBA). وقد تم تصميم وحدة تحكم باستخدام التحكم الضبابي الذي تم تنفيذه في إطار برنامج (knilumiS/baltaM). وتبين نتائج المحاكاة أن لسيارة معينة يوجد التطبيق الأمثل لقوة التعليق. مقارنة مع نظام (SBA) دون إدماج التعليق النشط، يمكن لنظام التحكم المقترح تحسين أداء نظام المكابح بشكل كبير.

كلمات مفتاحية *: التعليق النشط، النظام المانع للانغلاق، مسافة الكبح، التحكم بالمنطق الضبابي.*

Antilock Braking Systems (ABS) are now a commonly installed feature in road vehicles.

ABS is recognized as an important contribution to road safety as it is designed to keep a vehicle steerable and stable during heavy braking moments by preventing wheel lock. It is well known that wheels will slip and lockup during severe braking or when braking on a slippery (wet, icy, etc.) road surface. This usually causes a long stopping distance and sometimes the vehicle will lose steering stability. The objective of ABS is to manipulate the wheel slip so that a maximum friction is obtained and the steering stability (also known as the lateral stability) is maintained.

Typical ABS components include: vehicle's physical brakes, wheel speed sensors, an electronic control unit (ECU), brake master cylinder, a hydraulic modulator unit with pump and valves. Some of the advanced ABS systems include accelerometer to determine the deceleration of the vehicle.

The ABS control problem consists of imposing a desired vehicle motion and as a consequence, provides adequate vehicle stability. On the other hand, an active suspension is designed with the objective of guaranteeing the improvement of the ride quality and comfort for the passengers. The main difficulties arising in the ABS design and control are due to its high non-linearities and uncertainties presented in the mathematical model. For the active suspension control design is necessary to cope with the disturbance due to road friction which is unknown.

There are several works reported in the literature using fuzzy logic to a slip-ratio control of ABS, some examples are [1], [2], [3], [4]; a similar approach is used in the active suspension case [5, 6]. However, in most of the cases these two systems are treated independently.

The concept of integrating an Active suspension with an ABS system is in our interest.

The goal is to reduce the vehicle braking distance relative to a system equipped solely with an ABS system. This is achieved by increasing the vertical force exerted normal to the road surface in coordination with the application of the ABS. The active suspension will be a tool used to achieve the regulation of the normal force.

The rest of paper is organized as follows. The mathematical model for the longitudinal movement of a vehicle, including the brake and active suspension systems is presented in Section II. Section III presents the controllers for the two independent systems and then develops a coordination for the two inputs. The simulation results are presented in Section IV to verify the performance of the proposed control strategy. Finally, some conclusions are presented in Section V.

1. MATHEMATICAL MODEL

In this section, the dynamic model of a vehicle active suspension and ABS subsystems is revised. Here we consider a quarter of vehicle model, this model includes the active suspension, the pneumatic brake system, the wheel motion and the vehicle motion.

1.1. Quarter car model of an active suspension system

In this study, a simple quarter car suspension model that consists of one-fourth of the body mass, suspension components and one wheel is shown in figure 1. This model has been used extensively in the literature and captures many essential characteristics of a real suspension system.

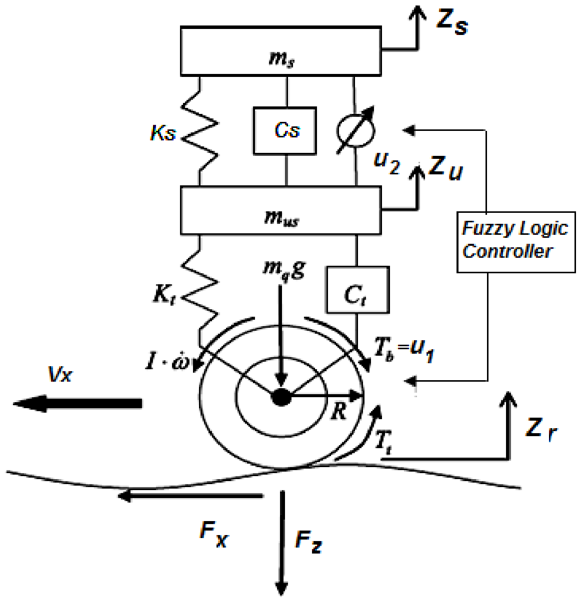


Figure 1 : Quarter vehicle active suspension model

The equations of motion for the sprung and unsprung masses of the quarter-car suspension model are given by:

$$m_s\ddot{z}_s = k_s(z_u - z_s) + c_s(\dot{z}_u - \dot{z}_s) + u_2 \quad (1)$$

$$\begin{aligned} m_u\ddot{z}_u &= -k_s(z_u - z_s) - c_s(\dot{z}_u - \dot{z}_s) \\ &- u_2 + k_t(z_r - z_u) + c_t(\dot{z}_u - \dot{z}_r) \end{aligned} \quad (2)$$

where m_s is the sprung mass, which represents the car chassis; m_u is the unsprung mass, which represents the wheel assembly; c_s and k_s are damping and stiffness of the uncontrolled suspension system, respectively; k_t serves to model the compressibility of the pneumatic tyre and Ct is the tire damping ; z_s and z_u are the displacements of the sprung and unsprung masses, respectively; z_r denotes road roughness and is regarded as disturbance to ASCS. u_2 is the control force.

As a result the normal force F_z can be written as:

$$F_z = m_q g + k_t(z_r - z_u) + c_t(\dot{z}_u - \dot{z}_r) \quad (3)$$

Where :

$$m_q = m_{us} + m_s$$

1.2. Modelling of an antilock braking system

The braking effect is due to the friction coefficient between tire and road surface. ABS maximizes the tire road friction force F_x which is proportional to the normal load of the vehicle F_z. The relationship between the road friction force and the normal force can be written as:

$$F_x = \mu_r F_z \tag{4}$$

The road coefficient of friction is the coefficient of proportion between F_x and F_z. It is a nonlinear function of wheel slip ratio λ, which is a well known parameter to represent slippage. The tire slip ratio is defined as:

$$\lambda = \frac{V_x - R\omega}{V_x} \tag{5}$$

Where V_x is the linear velocity of the vehicle; ω is the angular velocity of the wheel; and R is the radius of the wheel. The objective of ABS control system is to increase tire-road friction force by keeping the operating point of the car near the peak value of the μ-λ curve during the ABS maneuvers because this peak value in the nonlinear μ-λ curve is the only zone where the maximum friction will be achieved, so the desirable slip ratio is restricted in this zone. Figure 2 depicts nonlinear μ-λ curve for different road conditions.

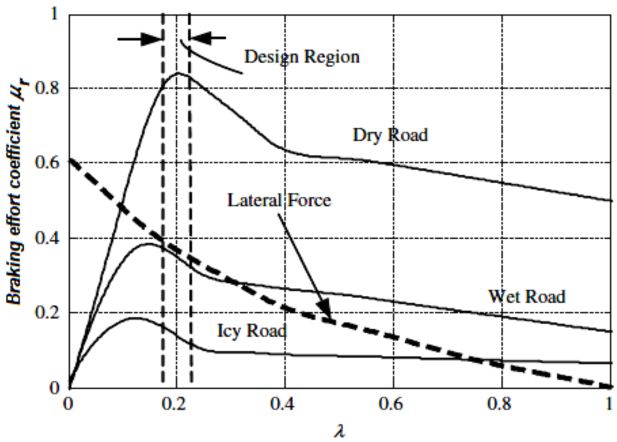


Figure 2 : Slip friction curves for different road conditions.

In this paper, the tire friction model introduced by Burckhardt (1993) and has been used. It provides the tire-road coefficient of friction μ_r as a function of the wheel slip λ and the vehicle velocity *Vx*.

$$\mu_r(\lambda, V_x) = \left[C_1(1 - e^{-C_2\lambda} - C_3\lambda\right] e^{-C_4\lambda V_x} \tag{6}$$

The parameters in equation (6) denote the following: C_1 is the maximum value of friction curve, C_2 the friction curve shape, C_3 the friction curve difference between the maximum value and the value at $\lambda=1$, and C_4 is the wetness characteristic value and in the range 0.02–0.04s/m. Table1 shows the friction model parameters for different road conditions.

Table 1 : Friction model parameters (Burckhardt (1993))

Surface conditions	C_1	C_2	C_3
Dry asphalt	1.2801	23.99	0.52
Wet asphalt	0.857	33.822	0.347
Dry concrete	1.1973	25.168	0.5373
Snow	0.1946	94.129	0.0646
Ice	0.05	306.39	0

Most manufacturers use a set point for the slipping ratio λ_d equal to 0.2 which is a good compromise for all road conditions.

The mathematical equations of the quarter vehicle dynamic equation can be given by:

$$m\dot{V}_x = \mu_r F_z \tag{7}$$

$$I\dot{\omega} = -T_b + \mu_r R F_z \tag{8}$$

where m is the total mass of the quarter vehicle; $\dot{V}_x$ is the linear acceleration of the vehicle; I is the wheel inertia and T_b is the braking torque.

From equation (5) the angular wheel velocity and the angular acceleration are calculated as:

$$\omega(t) = (1 - \lambda(t))\frac{V_x(t)}{R} \tag{9}$$

$$\dot{\omega}(t) = (1 - \lambda(t))\frac{\dot{V}_x(t)}{R} - \dot{\lambda}(t))\frac{V_x(t)}{R} \tag{10}$$

Using equations (7), (8), (9) and (10) and rearranging for yield

$$\dot{\lambda}(t) = -\frac{\mu_r F_z}{V_x}\left(\frac{1-\lambda}{m} + \frac{R^2}{I}\right) + \frac{R}{IV_x}T_b \tag{11}$$

Equation (11) clearly shows that, during braking, the slip ratio is dependent on the input torque u and the vehicle velocity V_x. In state space ; the system state variables are : $x_1 = S_x$, $x_2 = V_x$; $x_3 = \lambda$ where S_x is the stopping distance. The state space equations are

$$\dot{x}_1 = x_2$$
$$x_2 = \frac{\mu_r F_z}{m}$$
$$x_3 = -\frac{\mu_r F_z}{x_2}\left(\frac{1-x_3}{m} + \frac{R^2}{I}\right) + \frac{R}{Ix_2}T_b \tag{12}$$

The hydraulic brake actuator dynamics is modeled as a first-order system given by:

$$\dot{T}_b = \frac{1}{\tau}(-T_b + K_b P_b) \qquad (13)$$

where K_b is the braking gain; which is a function of the brake radius, P_b is the braking pressure from the action of the brake pedal which is converted to torque by the gain K_b.

During braking, it is assumed that the wheel radius is constant. Also, the vehicle speed V_x and the wheel angular velocity ω are available signals through transducers mounted on suitable places. So that the slip ratio λ, is an available parameter for the ABS closed-loop system.

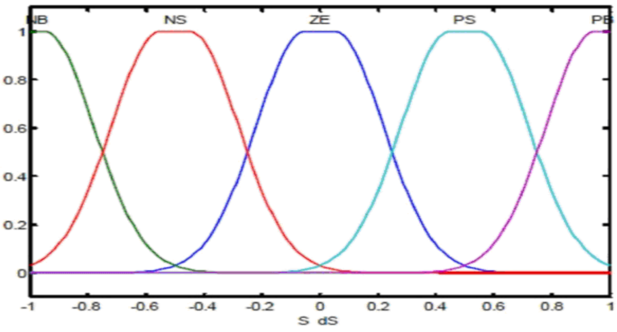
2. FUZZY LOGIC CONTROLLER

Unlike boolean logic, fuzzy logic can deal with uncertain and imprecise situations. Linguistic variables (SMALL, MEDIUM, LARGE, etc.) are used to represent the domain knowledge, with their membership values lying between 0 and 1.

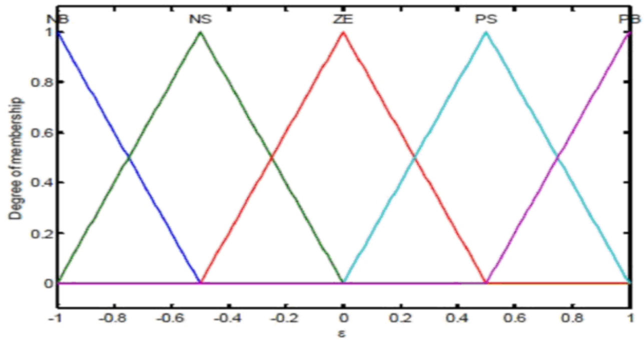
The same structure of FLC is used in the active suspension and the ABS. The control system itself consists of three stages: fuzzification, fuzzy inference machine and defuzzification. Fuzzification stage converts real-number (crisp) input values into fuzzy values, while the fuzzy inference machine processes the input data and computes the controller outputs in cope with the rule base and data base. These outputs, which are

fuzzy values, are converted into real-numbers by the defuzzification stage.

A Mamdani fuzzy logic controller with two inputs and one output is designed. The inputs and output are all divided into five fuzzy subsets: [NB, NS, ZE, PS, PB], where NB, NS, ZE, PM and PB mean negative big, negative small, zero, positive small and positive big, respectively. Gaussian and triangular shapes are selected for the membership functions of the inputs and the output, as shown in figure 3.



(a)



(b)

Figure 3: Membership functions for the: (**a**) inputs and (**b**) outputs.

Fuzzy rules have the following form: if *S* is *Ai* and is *Bi*, then ε is *Ci*, where *Ai*, *Bi* and *Ci* are linguistic variables. The fuzzy rules are listed in Table 2.

Table 2 : Rules of the fuzzy logic controller.

f(t)		Change in error, ė				
		NB	NS	Z	PS	PL
Error, e	NB	NB	NB	NM	NS	Z
	NS	NB	NM	NS	Z	PS
	Z	NM	NS	Z	PS	PM
	PS	NS	Z	PS	PM	PB
	PB	Z	PS	PM	PB	PB

3. SIMULATIONS AND RESULTS

To evaluate the performance of the proposed control, simulations were implemented in MATLAB/SIMULINK. Most of the model parameters used in the simulations are listed in Table 3. The vehicle was brought to a steady longitudinal velocity of 25 m/s (90 km/h) along a straight path and then the ABS was applied on the wheel.

The parameters of the quarter car model taken from [1] are listed below

Table 3 : Simulation parameters.

Symbol	Quantity	Value
m	Quarter vehicle mass	370 kg
R	Radius of wheel	0.3 m
I	Moment of inertia of wheel	1.0 kg.m^2

In this part, simulations were carried out with the Bang-bang and the proposed fuzzy logic ABS controller during emergency braking. The simulation results are shown in Figure 4, 5 and 6. Figure 4 illustrates the comparison of the slip ratio of the front wheel for different control. Figures 5 and 6 shows the stopping distance and vehicle velocity with the both ABS controllers.

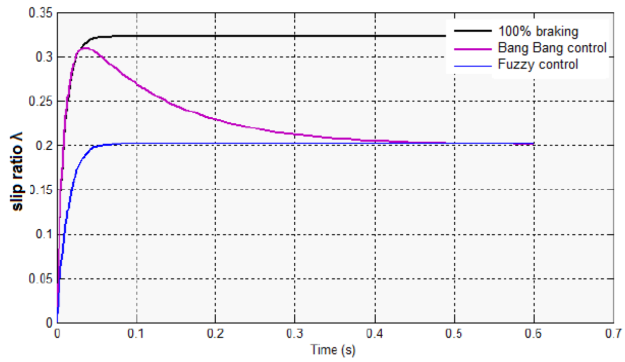


Figure 4 : Curve of the slip ratio λ of the tracking control.

There are two significant points to note from the simulation results. One is that the stopping distance is lower with a fuzzy logic controller than the bang-bang controller. The other being the wheel velocity is better controlled with the fuzzy logic controller. The variation in slip during the control process is minimal in the case of the fuzzy controller. This shows the fuzzy logic controller is ideally suited for the ABS systems, where better stopping distance and better controllability are its main aspects.

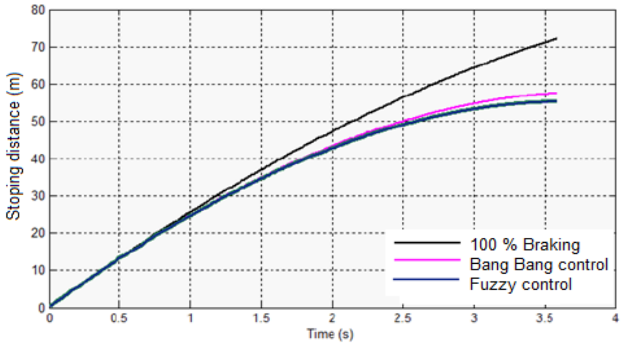


Figure 5 : Stopping distance for different control and normal road.

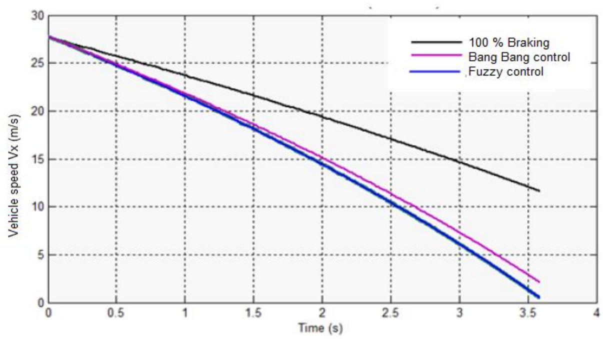


Figure 6 : Speed curves for different control and normal road.

The following table outlines the results for the control schemes designed above for the normal road/tire conditions illustrated as well as for a reduction in grip of 50%. All figures represent braking from 90 km/h under the assumptions detailed previously.

Table 3 : Performance Figures for Various ABS Schemes

	Normal Road-Tyre Conditions		**Wet road (50% Reduced Grip)**	
ABS Controller	**Distance (m)**	**Time (secs)**	**Distance (m)**	**Time (secs)**
100% Braking	84	5.5	125	8.2
Bang-Bang Control	55.5	3.6	82.5	5.4
Fuzzy Control	55	3.5	51.5	4.3

CONCLUSION

In this work fuzzy logic based controller for ABS assisted with active suspension has been proposed. The simulation results show that, compared with a conventional bang-bang ABS controller, the braking performance of the vehicle has been improved with the proposed FLC

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