A fuzzy logic-based Anti-Lock Braking Systems

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Abstract: *In today's automobile industry, the need to adjust the speed of the vehicle and stabilize the wheels control is still a task due to road conditions and traffic. The Anti-lock Braking System (ABS) is a tool used in automobiles to prevent wheels from locking while brakes are pressed. The objective of this work is the maintenance of the wheel slip value to a desirable slip ratio as the vehicle model is simulated using a fuzzy logic controller. The analyses are made based on the slip ratio, angular velocity and stopping time.*

***Keywords**:* FUZZY LOGIC CONTROLLER, ANTI-LOCK BRAKING SYSTEMS, TIRE MODEL, FRICTIONAL FORCE

1. Introduction

The industries of car manufacturing have always struggled to provide the best driving experience and yet one of the challenges of their work is ensure total safety. Among all the features a vehicle includes there is still a lot of improvement to be done on the systems that control its movement. Anti-Lock Braking system (ABS) [2, 4-6, 8, 10-12] is one of these features which nowadays is a pre-attached technology to the brakes implementation to prevent wheels from slipping while rapid stops. Road surface conditions may vary therefore an active system is required to stabilize the vehicle after the driver has lost steering control. The friction between tires and the road surface tends to be reduced after the brakes are pressed. It is an ABS system's duty to detect the locked wheels and to quickly release the brakes. In this way the vehicle's drift could be avoided so technically the drivers also the vehicles safety would be provided. Basic functionality of braking includes shorten stopping distance, steerability during braking through ABS system and stability during braking to avoid overturning. In this study, Fuzzy Logic [1] has been used as an adaptive controller for the simulated system model in order to enhance the performance of the vehicle).

The organization of the paper is as follows: In session 2 we describe the anti-lock braking system background and its components and a practical idea of how it is implemented in vehicles. It also describes the mathematical model of the non-linear quarter tire model and provides the details of the respective functions for the essential features. Session 3 will introduce Fuzzy Logic and a discussion on its application for the ABS system. The developed Simulink model of the Fuzzy controlled ABS system will be represented in session 4. Detailed analyses and the numerical results will be provided in session 5. Finally, conclusions and recommendations for future work will be emphasized in session 6.

*2. Anti-Lock Braking System**Грешка! Източникът на препратката не е намерен.***

The ABS System [7, 9] also known as anti-skid braking system is an automobile safety system that prevents the lock of the vehicles wheels as the brake pedal pressure is applied. Considering the emergency cases that can happen in traffic or under different circumstances where the road's surface might be very unpredictable, slippery or uneven it is necessary that the driver would be able to maintain the control of steer and vehicle stability on short distance stops. Ideally, while a vehicle is in motion, when brake pedals are hardly applied, this system would reduce the wheel speed and provide the shortest stopping distances.

Let us emphasize how the brake system works. The braking process starts when the driver commands the brake pedal position which is translated into a brake pressure by the electronic control unit. The brake pressure results in a braking force on the brake disc which becomes a braking wheel torque at the wheel. The braking torque on the wheels creates a negative longitudinal force to decelerate the vehicle. Thus, the moment the driver hits the brake pedal it applies pressure at the hydraulic system that causes brake pedals to squeeze against the discs. That causes the vehicle to slow down by reducing the speed of both vehicle and the wheels. An important indicator of a vehicle speed is slipping ratio. The difference in the wheel speed and vehicle speed is defined by this factor.

$$\text{Slip ratio}=\frac{\text{vehicle speed}-\text{wheel speed}}{\text{vehicle speed}}\ \text{x}\ 100\% \qquad (1)$$

The implementation of the system is as illustrated in **Fig. 1**

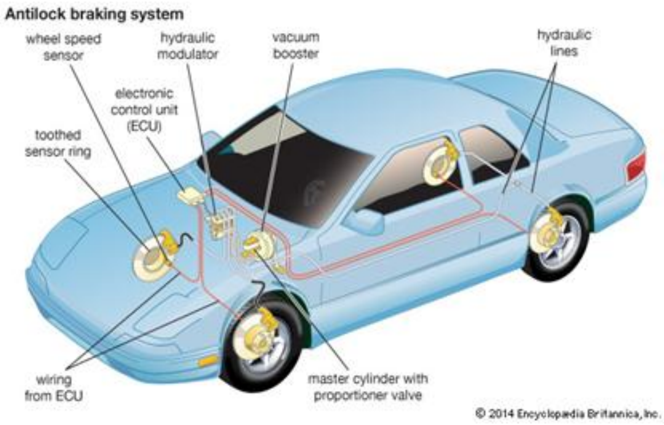


Fig. 1: *ABS System Components.*

The four main components are speed sensors, a pump, pressure release valves and controller. The sensors which are a combination of a toothed wheel, electromagnetic coil or magnet and a Hall Effect Sensor are used to calculate the acceleration and deceleration of the wheel. The toothed wheel is fitted to the rotating wheel hub proximately close to the magnetic sensor. There are four sensors, one per each wheel and sometimes they are placed on the differential. The sensor primarily detects a change in acceleration in the longitudinal direction of the vehicle and outputs it to the ABS control module. The Electronic Control Unit, shortly known as ECU is the controller that receives information from each individual speed senor. In case it receives a signal from the sensor that a wheel has lost friction with the ground, it activates the ABS modulator.

The ABS system detects the right moment when a specific wheel is about to lock after the brake pedal is hit and the wheel speed is being reduced rapidly than the rest and quickly opens a pressure release valve in the hydraulic system that reduces the brake pressure on this specific wheel. The system automatically does this process in pulse form to prevent the wheels from locking. The modulator actuates the braking valves on and off. Hence, the pressure in the brake pipe is lowered. The wheel begins to rotate faster and tends to achieve the same speed as the rest. The valves might be separated in some systems or combined in others and they might work in three different positions. In either case, they communicate with the controller and the pump to add or release pressure from individual wheel brakes. The modulator valve has an addition hold phase more like a cycle (5-6 times per second) which maintains pressure till the vehicle comes to a controlled stop. This process might be repeated continuously until the wheels reach equal speed. The valves suffer from clogging problems which causes them to have difficulty in opening, closing or change position. Thus the system might result in failure due to inoperability of the valves and the valves should be frequently checked. As discussed above the other component of the system was the pump. Once the pressure is released from the valves of the system, it needs to be restored on the individual wheel brakes when required. The pump status is adjusted by the controller in the required pressure level. While pump is cycling the driver might experience some vibration on the pedal. The cycling happens at a range of milliseconds thus the vibration is naturally felt.

2.1 Mathematical Model

In this session a briefly explanation of the mathematical formulation for the model is provided considering a simplified quarter vehicle model (**Fig. 2**). We begin by developing the linear braking model parameterized according to the Pacejka model (2002)[9] known as Magic Formula. Table 1 shows the notations used below.

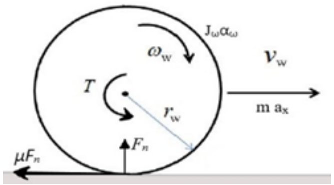


Fig. 2: *Quarter car model.*

Table 2: *Notation used in problem formulation.*

Notation	Meaning
α_ω	Wheel angular acceleration
a_x	The linear acceleration
F_n	Vertical force
V_x	Vehicle linear velocity
ω	Angular velocity
R	Radius of tire
λ	Wheel slip
m	Mass of tire
T_b	Braking torque
a, b, c	Road coefficients
T_d	Actuator Time delay
J	Inertia

The torque at the wheel center is as given above:

$$J_\omega \alpha_\omega = \mu R F_n - T_b \tag{2}$$

$$m a_x = - \mu \times F_n = m\frac{dVx}{dt} \tag{3}$$

$$\lambda = \frac{Vx - \omega R}{Vx} \tag{4}$$

$$\mu_x = a(1 - e^{-b\lambda} - c\lambda) \tag{5}$$

$$T_d = e^{-\tau s}\frac{a}{s+a} T_{ref} \tag{6}$$

3. Fuzzy Logic Controller

The performance of the proposed model has been tested against general variations in road conditions. The theory of fuzzy sets and rules that was initially developed by Zadeh can be used to evaluate these imprecise linguistic statements directly. Considering the easy adaptation of fuzzy logic controller to varying road surfaces, traffic or uneven pavement the implementation of this controller for the actual model would give us some benefits. When compared to other types of controllers, Fuzzy controller has shown better performance and effectivity. This soft computing system doesn't need a precise model. Moreover Fuzzy logic has the ability to make decision even with uncompleted information and provides effective means of capturing the approximate nature of the physical world and human-way of thinking logic. In this study we use MATLAB environment as a useful tool to determine the Fuzzy rules for the Fuzzy Inference System. The purpose of the controller is to keep the slip at a desirable optimal value 0.1. The method we have used is Mamdami as shown in Fig. 3.

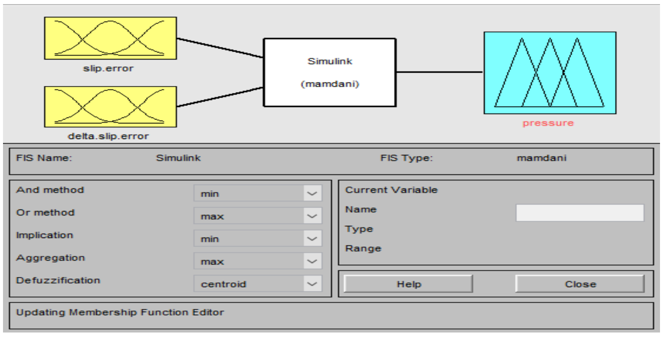
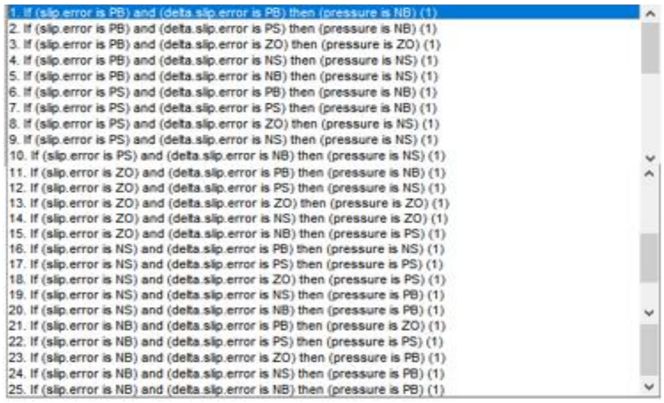


Fig. 3: *FIS for the proposed model.*

The FIS has two inputs, respectively the first one determines slip error values (actual slip minus the fixed slip ratio of 0.1) and the second is the difference rate in slip error which is the vehicle deceleration. Nomenclature used for the rule base is as follows: NB -Negative Big | NS– Negative Small ZE- Zero | PS – Positive Small | PB –Positive Big

Rules are determined in **Fig. 4**.



1. If (slip.error is PB) and (delta.slip.error is PB) then (pressure is NB) (1)
2. If (slip.error is PB) and (delta.slip.error is PS) then (pressure is NB) (1)
3. If (slip.error is PB) and (delta.slip.error is ZO) then (pressure is ZO) (1)
4. If (slip.error is PB) and (delta.slip.error is NS) then (pressure is NS) (1)
5. If (slip.error is PB) and (delta.slip.error is NB) then (pressure is NS) (1)
6. If (slip.error is PS) and (delta.slip.error is PB) then (pressure is NB) (1)
7. If (slip.error is PS) and (delta.slip.error is PS) then (pressure is NB) (1)
8. If (slip.error is PS) and (delta.slip.error is ZO) then (pressure is NS) (1)
9. If (slip.error is PS) and (delta.slip.error is NS) then (pressure is NS) (1)
10. If (slip.error is PS) and (delta.slip.error is NB) then (pressure is NS) (1)
11. If (slip.error is ZO) and (delta.slip.error is PB) then (pressure is NB) (1)
12. If (slip.error is ZO) and (delta.slip.error is PS) then (pressure is NS) (1)
13. If (slip.error is ZO) and (delta.slip.error is ZO) then (pressure is ZO) (1)
14. If (slip.error is ZO) and (delta.slip.error is NS) then (pressure is ZO) (1)
15. If (slip.error is ZO) and (delta.slip.error is NB) then (pressure is PS) (1)
16. If (slip.error is NS) and (delta.slip.error is PB) then (pressure is NS) (1)
17. If (slip.error is NS) and (delta.slip.error is PS) then (pressure is PS) (1)
18. If (slip.error is NS) and (delta.slip.error is ZO) then (pressure is PS) (1)
19. If (slip.error is NS) and (delta.slip.error is NS) then (pressure is PB) (1)
20. If (slip.error is NS) and (delta.slip.error is NB) then (pressure is PB) (1)
21. If (slip.error is NB) and (delta.slip.error is PB) then (pressure is ZO) (1)
22. If (slip.error is NB) and (delta.slip.error is PS) then (pressure is PS) (1)
23. If (slip.error is NB) and (delta.slip.error is ZO) then (pressure is PB) (1)
24. If (slip.error is NB) and (delta.slip.error is NS) then (pressure is PB) (1)
25. If (slip.error is NB) and (delta.slip.error is NB) then (pressure is PB) (1)

Fig. 4: *Rule base for the two inputs*

The Fig. 5 describes the relation of pressure as output and the two input data.

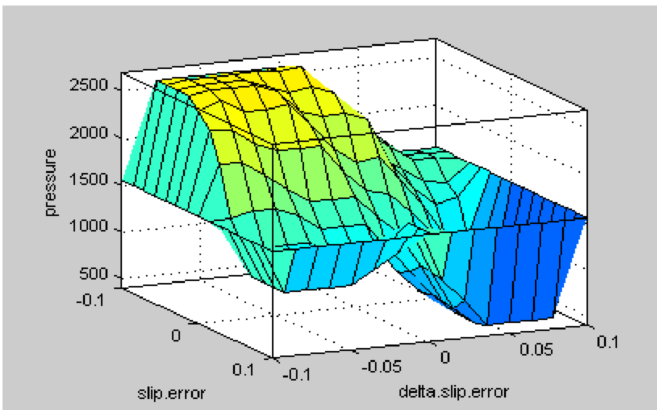


Fig. 5: *Surface viewer for the fuzzy inference system.*

4. Fuzzy Controlled ABS Simulink model

In this session we tend to use as a nonlinear control scheme the fuzzy controller attached to the tire model proposed for the ABS system. The corresponding data for subsystems values are put in MATLAB source code. Fuzzy logic Controller block is linked with the FIS we described in session III. Figure 6 shows the full Simulink vehicle model.

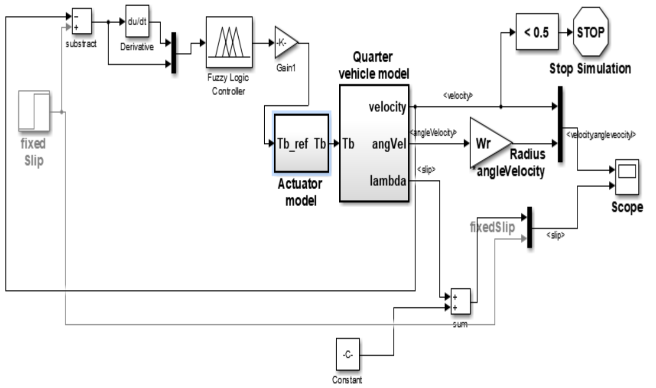


Fig. 6: *Simulink vehicle model.*

The actuator subsystem refers to the equation (6) which is a first order model used for simplifying the design, where Td is the actuator time delay and the Ts is the saturated value, the parameter a is a pole set to a value of 70. The second subsystem is the tire model described by the equation (5) of the longitudinal friction coefficient where λ is the slip value and coefficient a, b, c determine road conditions. The fixed slip value is set to 0.1 refereed to the Pacejka tire model. Test are made on dry asphalt condition as we have emphasized earlier.

5. Simulation Results

After the simulation of the model we continue to describe the graphics that we derived. **Fig. 7** shows the deceleration of the vehicle.

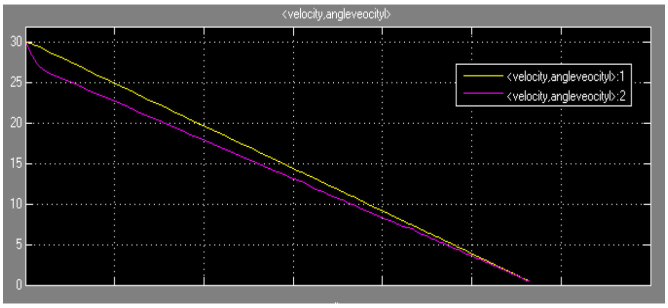


Fig. 7: *Model results for velocity deceleration*

As we can see from the graphic lines, the starting value is a velocity of 30km/h given by the yellow line. The stopping time is approximately 2,80 seconds where the vehicle comes at halt. This is a great value compared to other controller systems. Fuzzy Logic controller tends to respond faster when brakes are applied. Thus, it could make this controller more preferable to other systems.

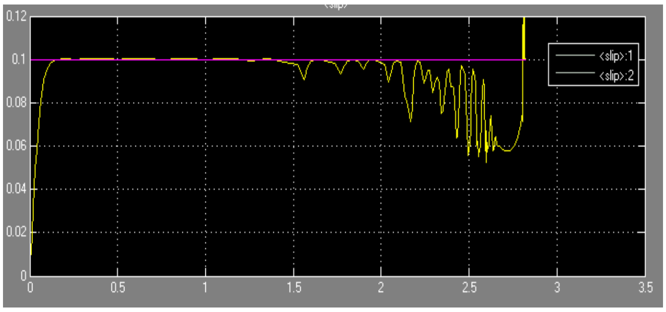


Fig. 8: *Slip Ratio*

From the **Fig. 8,** we can observe the desired slip ratio of the vehicle once the brakes are pressed. We can see the curves of its line as is rises up to a fixed desired slip value. This settling time is approximately 0,15 seconds which is still a very short time when compared to other controllers. We can strongly emphasize that the system stabilization is achieved faster and fuzzy controlled systems are more robust.

6. Conclusions

ABS system control is treated as a nonlinear system designed with a soft computing controller as it is fuzzy logic controller. In this work, we use this controller to define the required parameters as slip ratio and angular velocity. The simulation results showed the good performance achieved when using fuzzy logic controller. This is due to its ability to provide shorter stopping distance and smaller slip ratio of the vehicle as the brakes are pressed. The fixed slip ratio of 0.1 has shown good results in ABS system model. The stopping time is quite small and this system performs better than some other works with different controller for the ABS system. Further consideration must be taken in the future and other simulations with different road condition will be performed.

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