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Applying Active Force Control with Fuzzy Self-Tuning PID to Improve the Performance of an Antilock Braking System

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ABSTRACT

One of the safety devices in ground vehicles is anti-lock brake system (ABS) that works to prevent wheel lockup when sudden braking happen. The existence of this system in the vehicles gives it the power to control the pressure level in order to preserve the stability of the wheel slip and hence of the vehicle. Though, the ABS displays vigorous nonlinear behavior at any point, the vehicle fitted with the controller might have a propensity for instability. This paper presents a new robust control approach based on an active force control (AFC) loop coupled with a self-tuning fuzzy logic (FL) based proportional-integral-derivative (PID) control scheme for the effective performance of the proposed ABS through the simulation analysis. To achieve a satisfactory result in the controller, both the FLPID and FLPID-AFC schemes are simulated and compared. The results is clear that, relative to the FLPID with the AFC scheme displays a quicker and better response under different operating conditions and loads compare with the FLPID controller. The implementation of the AFC-based controller into the ABS offers robust and stable performance that is capable of being deployed on the ground vehicle in a real-time and workable system.

Keywords: Anti-lock brake system, Active force control, PID controller, Fuzzy self-tuning

1. INTRODUCTION

The Anti-lock brake system (ABS), is the most widely system in the ground vehicles for the safely purpose, and is working to increase the generation of brake force between the tires and the road surface while preserving vehicle stability during braking. It is also well understood that the ABS system adds to the vehicle the ability to maintain steering during an unexpected stop with the intermittent stopping mechanism of this type of system and prevent the wheel from locking during braking. Nevertheless, there are selected restrictions as: unstable slip behaviour at friction points, several studies are useful for evaluating and error tuning the ABS mechanism. It begins to activate as the wheels start to lock-up. The vehicle's steering would then become faulty, making it impossible to manipulate the steering wheel correctly for long durations, resulting in severe accidents. ABS does not shorten the stopping time by itself, but it does aid in keeping the vehicle under balance while sudden braking. Ground vehicles with high speeds have become more popular as a result of the high demand for this style of vehicle from consumers. As a consequence, emphasis on safety has become crucial. Previously, the anti-lock braking mechanism proposed to minimize the aircraft's stopping distance, and it has since been deemed one of the most common safety methods offered on most recently sold ground vehicles due to their high assistance, helping drivers to stop the vehicle in the safest possible manner. As a

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consequence, road conditions have a significant impact on system parameters; ABS performance cannot always be sufficient and appropriate. In addition, noise and high uncertainty are the most common sensor-related problems [1].

Due to the interaction between the tire and the surface of the road, high nonlinearity, the instability in the dynamics of the vehicle that is always there and uses the standard PID controller might not be as stable as needed to deal with the controller in this type of dynamic system. Intelligent active force control (AFC) is trying to strengthen it by merging this technique with PID by using artificial intelligence techniques to track the suitable percentage slipping. Active Force Control (AFC), a sophisticated and robust technique, has been proposed and shown to be much superior in the control of different dynamic systems compared to the conventional PID control method [2]. This method has been validated on an active suspension system in the lab, and the findings indicate that it improved dynamic performance [3-5]. It uses experimentally with semi-active quarter-car suspension by integrating it with Sliding mode, using fuzzy logic techniques to change the power gains in sliding mode method [6]. The findings show that performance is robust in the suggested fuzzy controller. The system has been used in ABS and has demonstrated promising outcomes in vehicle behaviour control during panic braking and provides the optimal sliding coefficient ratio to keep the wheel from being completely locked under nonlinearity, parametric uncertainty [7]. Quanser aero twin-rotor model [8], has also been suggested experimentally with IAFC-based controller in a mechatronic test rig to evaluate the applicability and efficacy. Spacecraft pitch attitude control using the technique improved with a PD controller with two degrees of freedom showed promising effects on the system [9]. There are several techniques that can be found in the literature, which can be classified as adaptive methods, which are based on algorithms.

Several researchers used different control mechanisms to enhance the ABS phenomenon, and one was the use of a fuzzy logic control system (FLC). Another more sophisticated control technique applied to the ABS is a fuzzy logic PID control (FLPID) modelling method, also known as a hybrid control technique focused on the combination of fuzzy control and conventional PID control approaches. FLC has a range of benefits. For example, it is inexpensive, simple to implement, and applicable to non-linear dynamic systems. Therefore, it has been used in many applications [6, 10, and 11]. The other more complex control solution applied to ABS with fuzzy logic PID control (FLPID) was developed as a hybrid control system based on the combination of fuzzy control and conventional PID control system. The accomplishment of the control scheme for FLPID, is using fewer fuzzy rules than the preliminary FLC [10]. FLC suggested for the half-car active suspension model [12] and quarter car suspension model [13], to compare its performance to the system. In terms of RMS and settling time, the FLC has outperformed passive and PID controlled systems. Latest study using an AFC-based hybrid control system has been extended to ABS [14-16], by improving other control systems with optimistic output enhancement.

2. THE SYSTEM FRAMEWORK

In the presence of braking conditions, the single wheel model in Figure 1 defines the quarter vehicle model for the experimental phase that illustrates the vehicle's linear motion and the vehicle wheels' rotational motion [17, 18]. This research platform enables for laboratory testing, since it represent the actual concept for a brake system dynamic.

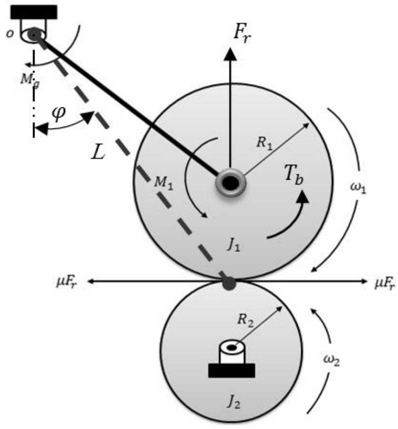


Figure 1. Quarter-vehicle platform.

The equations of the dynamic system of the proposed model, is based on the second law of Newton [19, 20], beginning with the upper and lower wheels as follow:

$$J_1\dot{\omega}_1 = F_t r_1 - (d_1\omega_1 + S_U + T_B) \tag{1}$$

$$J_2\dot{\omega}_2 = -(F_t r_2 + d_2\omega_2 + S_L) \tag{2}$$

In equation Eq. (1) as well as Eq. (2), the tractive force refers to the friction factor on the road multiplied by the Coulomb coefficient:

$$F_t = \mu(\lambda)F_r \tag{3}$$

The other kind of force acts vertically on the point of contact between the wheel and the road and is defined:

$$F_r = \frac{d_1\omega_1 + S_U + T_B + M_g}{L\left[\sin\theta - \mu(\lambda)\cos\theta\right]} \tag{4}$$

The angle φ position as shown in Figure (1), is between the normal at point (o) and the hidden line L. The slippage between the wheel and the asphalt surface occurs when the wheel is subjected to more force. The braking torque TB in this model can be written as:

$$\dot{T}_B = -c_{31}T_B + c_{31}b(u), b(u) = \begin{Bmatrix} b_1 u + b_2, if\,(u \geq u_o) \\ 0, if\,(u < u_o) \end{Bmatrix} \tag{5}$$

Where c31, b1, b2 uo are constant as 20.37, 15.24, -6.21, and 0.42 respectively. The relationship between the DC motor's control input implements is described by *b*(u), which is assumed for the actuator. The operation of the brake pads is powered by this motor, where u is the constant input, and the braking torque T_B is generated [18].

$$\lambda = \frac{R_2\omega_2 - R_1\omega_1}{R_2\omega_2}, \left(\omega_2 \neq 0\right) \tag{6}$$

$$\mu(\lambda) = c_1\lambda + c_2\lambda^2 + c_3\lambda^3 + \frac{c_4\lambda^p}{a+\lambda^p} \quad (7)$$

In terms of the coefficient of friction between the wheel and the road, see Figure 2, the estimated relationship is shown by the proposed formula [18] for the coefficient of road adhesion vs. wheel slip values, as shown in Table 1.

Table 1 Cast iron surface condition parameters [18]

Symbols	Values
c1	-0.04240011450454
c2	0.00000000029375
c3	0.03508217905067
c4	0.40662691102315
a	0.00025724985785
p	2.09945271667129

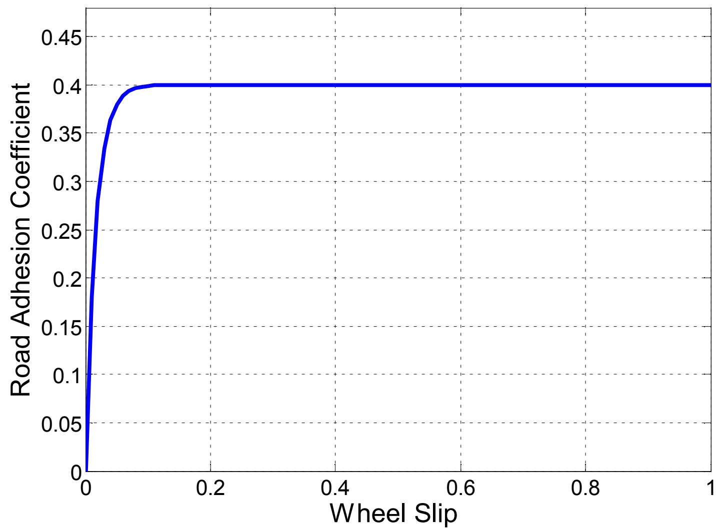


Figure 2. Curve of road condition.

2.1 PID Controller

The widely controller used in control loops and the process control industries, is the Proportional-Integral-Derivative controller. Although it reduces the uncertainty of passive dynamic, but still the dynamic system's response through the PID controller is slow and the performance needs to be enhanced. The PID control algorithm's transfer function can be written as follows:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{d}{dt} e(t) \quad (8)$$

and; *Kp*: proportional gain tuning parameter; *Ki*: integral gain tuning parameter, and *Kd*: derivative gain tuning parameter.

2.2 Self-Tuning PID based Fuzzy Control

The proposed scheme, which uses first order Takagi-Sugeno (T-S) fuzzy structures, is introduced in this section as a tuning-tool for each of the PID control gains. The proposed scheme can be easily implemented for either linear or nonlinear systems [10]. The proposed fuzzy self-tuning model contains three decoupled fuzzy systems; each of the corresponding parameters in the PID controller, see Eq. (7).

The error and error improvements are used as closed-loop performance behaviour-recognizers. In the closed loop structure of the ABS, they are available signals and do not require extra hardware. It is possible to express the self-tuner as:

$$
\begin{aligned}
K_P &= FS_1\left[e(t),\dot{e}(t)\right],\\
K_I &= FS_1\left[e(t),\dot{e}(t)\right],\\
K_D &= FS_1\left[e(t),\dot{e}(t)\right]
\end{aligned}
\tag{9}
$$

The resulting controller signal is produced when the fuzzy module is connected to the actual PID elements in parallel, as shown in Figure 3, where the fuzzy module tries to recognize when the relevant parameter is not correctly tuned and then attempts to adjust it to produce better performance.

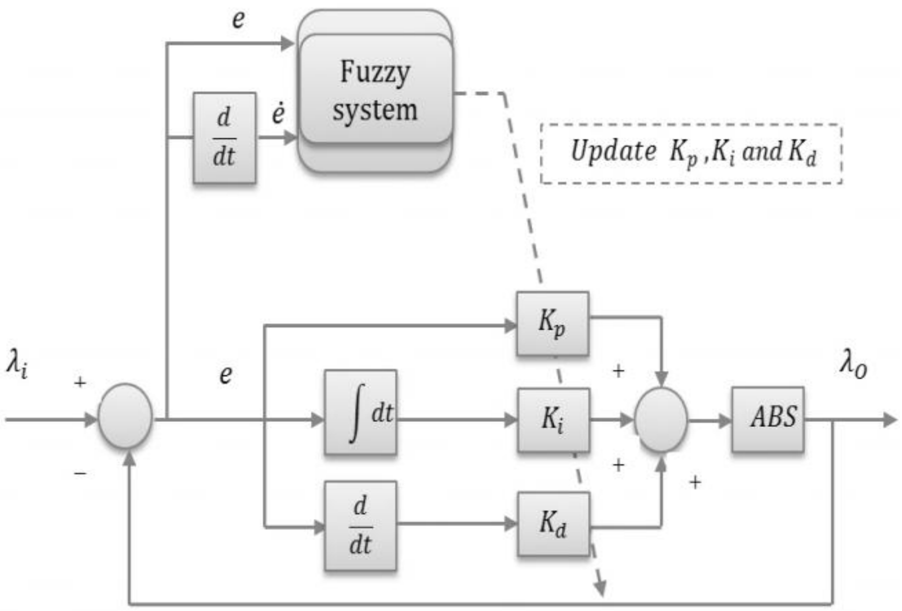


Figure 3. Self-tuning PID based fuzzy controller.

To synthesize each module, a T-S style fuzzy method is used. The following form has a typical rule:

IF y1 IS A and y2 IS B THEN z1 = f (y1, y2), z2 = f (y1, y2) and z3 = f (y1, y2) .

Where A and B are fuzzy sets in the setting, the consequence is that z1=f (y1, y2), z2=f (y1, y2) and z3=f (y1, y2) are functionally crisp. The fuzzy system can be defined with this structure as two input three output fuzzy systems. Three Gaussian membership functions are used to normalize the inputs, e and ė in the proposed self-tuner. As seen in Table 2, the nine laws are the rule base for each module: negative N, positive P, negative big NB, positive big PB, negative small NS, positive small PS, positive medium PM, and zero ZE.

Table 2 The nine rules of Fuzzy logic technique

de/dt	NB			ZE			PB		
e	*Kp*	*Ki*	*Kd*	*Kp*	*Ki*	*Kd*	*Kp*	*Ki*	*Kd*
NB	NS	PS	PB	NB	PS	PS	NS	PS	PS
ZE	NS	PS	PB	PB	PS	ZE	PS	PM	PB
PB	NB	PS	PS	PB	PS	PS	NS	PS	PB

There are two inputs and three outputs in this controller, as shown in Figure 4.

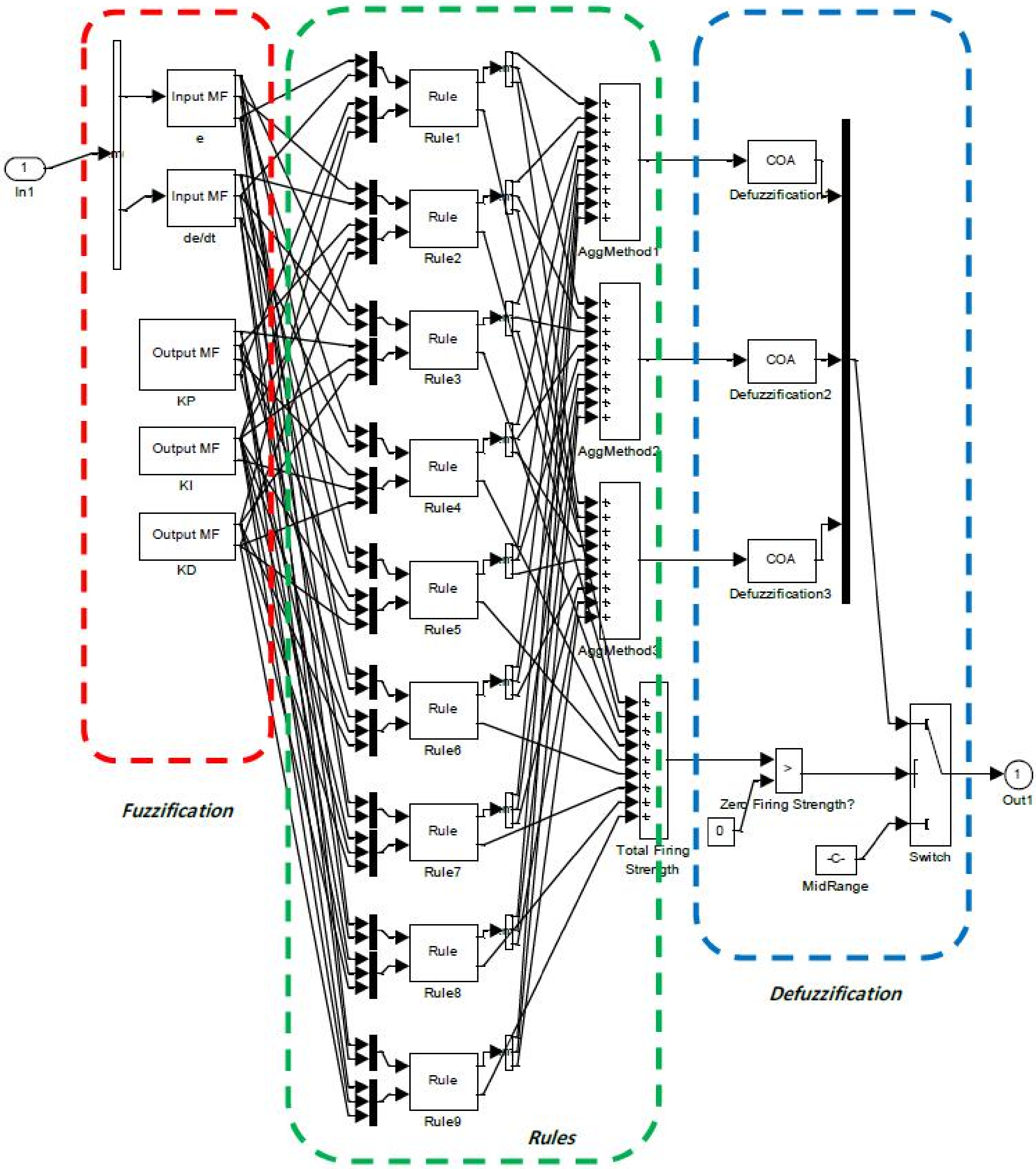


Figure 4. Fuzzy tuning rules scheme.

2.3 Active Force Control (AFC)

The research on this technique is initiated and presented in compact form by Hewit and Burdess (1981). The approach of the AFC is primarily based on the invariance principle and Newton's second law of motion. Research has demonstrated that it is possible to develop a feedback controller to ensure the robustness and reliability of dynamic system regimes despite the existence of external disturbances or varying operational and loading conditions that can accompany the output of the system [21-23]. The AFC technique, which is essentially derived from Newton's second law of motion [2], such as a rotating mass, is based on the following principle:

$$\sum T_{total} = J\alpha \tag{10}$$

The purpose of this control system is to control the dynamic system in order to ensure that the integrity of the system is retained even in the case of sudden external disruptions [2]. It is dependent on the inertia or mass gain that must be estimated for the proposed dynamic system, with calculation of the force or acceleration signals caused by the system [6, 12]. Following the ABS, the equation of motion that would be paired with the AFC methodology is:

$$T_B - Q = J_1\dot{\omega}_1 \tag{11}$$

The AFC theory was extended to the ABS, as seen in Figure 5.

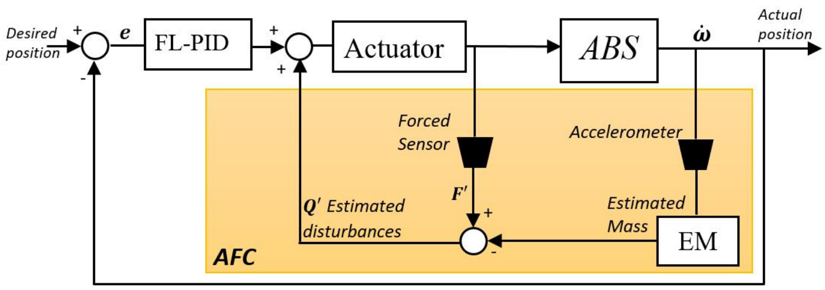


Figure 5. AFC concept applied to the system.

The physical quantities that must be measured directly from the dynamic system are the actuating force and vehicle acceleration that certain sensing components can achieve. By the equation [5, 7, 14 -16], the estimated disturbance torque Q' can be calculated:

$$Q' = \frac{T_B}{R_1} - E_m\dot{\omega}_1 R_1 \tag{12}$$

In this work, using MATLAB/Simulink to implement the AFC method to the ABS and which has been carried out using the (s-function) process. The comparison study was ready to improve the classic PID with the robust techniques in this paper in the same way as other closed-loop control systems. The objective of this control strategy is to make sure that the system remains stable and robust however in the presence of external disturbances that could impact the system unexpectedly during the braking case operation, varying from road conditions to the external environment temperature. Figure 6, illustrate the technique merge with the scheme control based Simulink block diagram.

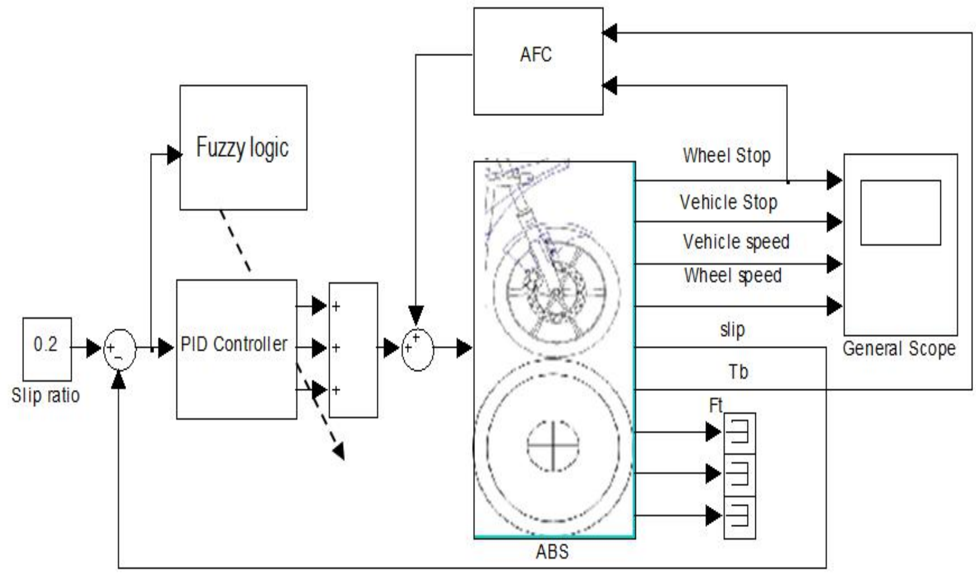
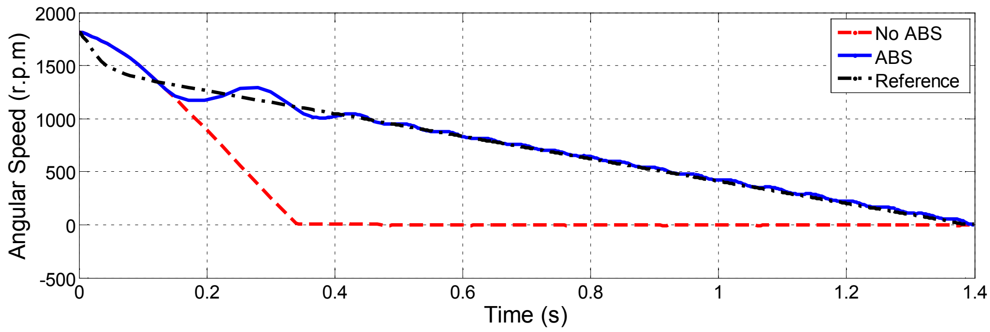


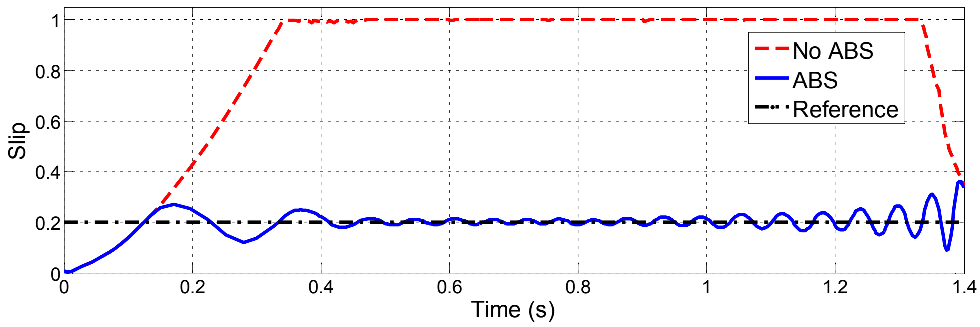
Figure 6. The simulink block diagram of FLPID-AFC scheme.

3. RESULTS OF VALIDATION

The brake model was simulated using the MATLAB/Simulink (s-function) method, then combined with both the FLPID controller and the AFC loop, as seen in Figure 6. The passive dynamic action with the simulation parameters [18, 19] is simulated as follows: Upper wheel radius = 9.95×1e-2 m, lower wheel radius= 99×1e-3 m, rotational inertia for the upper wheel= 7.5×1e-3, rotational inertia for the lower wheel = 25.603×1e-3, the coefficient of friction of both upper and lower wheels are 1.2×1e-4, and 2.25×1e-4, standard level of slip=0.2, while the static friction in the upper and lower wheels are 3×1e-3, and 93×1e-3, and the gravitational moment acting on the equilibrium lever =19.62. The PID controller's gains are tuned heuristically. The gains were used to achieve the required values for the dynamic system are: 28, 19, and 0.6 for the P, I, and D gains, respectively. Figure 7(a), displays the wheel speed and slip ratio under 1800 r.p.m (67 km/h) respectively during panic braking with/without ABS.



(a)



(b)

Figure 7. Braking during the panic (no ABS), (a) wheel angular speed and (b) wheel slip ratio.

By using the brake feature without the ABS model, the wheel speed drops to zero after 0.3 seconds of braking force, and the braking case is locked at the begin. For ABS, the wheel does not lock-up until the vehicle gets to a complete stop on road. With no ABS, the wheel's slip ration results in a slip value of 1 within 0.3 seconds, as seen in Figure7 (b), while it functions keep the wheel within the slip ratio to the end of stopping. The ABS passive dynamic behaviour of the system is illustrated in Figure 8(a). During sudden braking, the wheel speed instability behaviour denotes the inability to steer the directing vehicle. Figure 8 (b) illustrates the system's stable behaviour as a result of the FLPID schemes implemented, which keeps the system stable over the vehicle stopping distance.

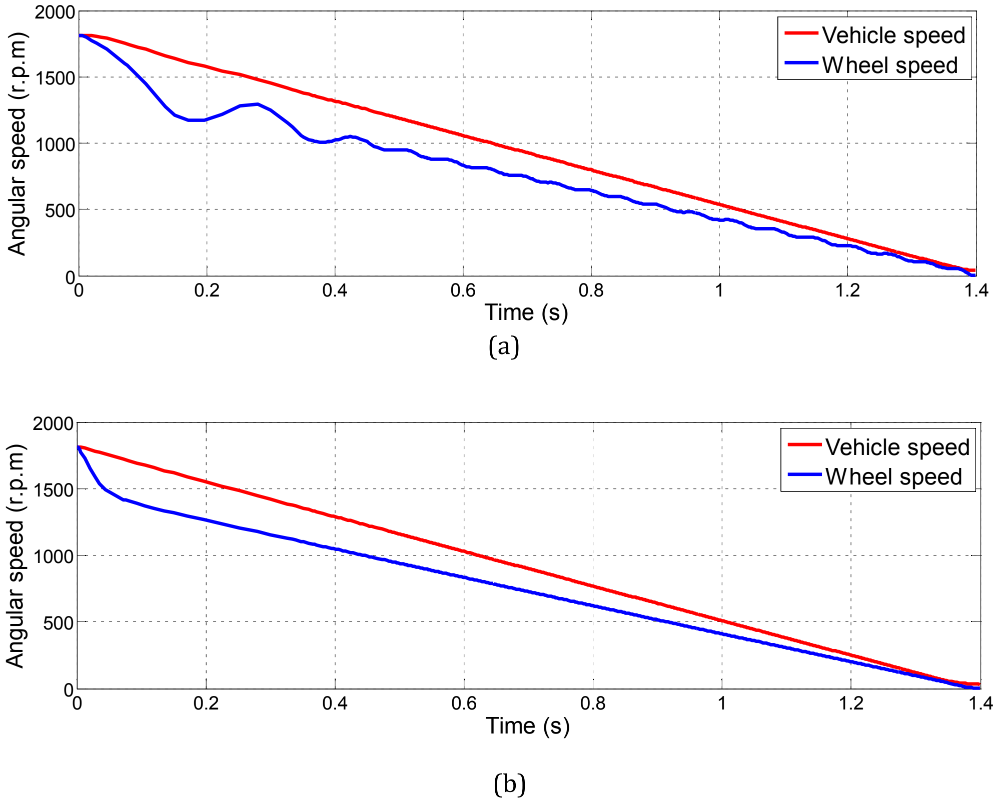


Figure 8. Speed of the vehicle vs. wheel during panic braking (a) ABS Passive Dynamic System and (b) FLPID with Dynamic System.

There is a need to select the approximate mass (EM) for the dynamic system. And, as seen in Figure 9, the value of slip ratio is always between 0 and 0.2. Some approximate mass (EM) values ranging from (0.9-8.0) kg have been used, and it turns out that the system reacts effectively with reducing in mass value before it is stable at 0.9 kg.

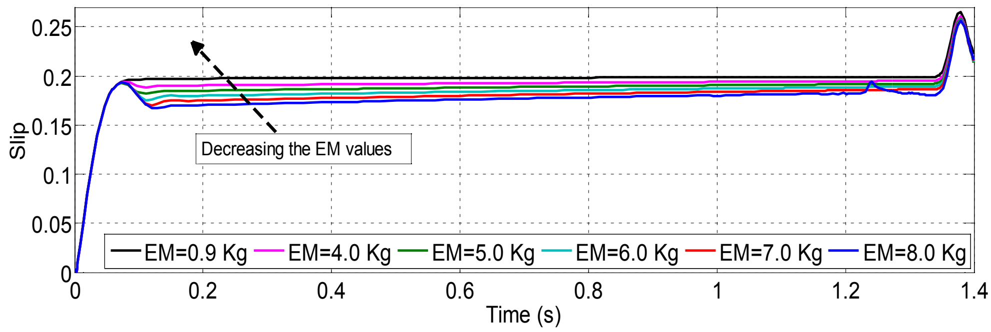


Figure 9. Slip ratio with different EM values.

Consequently, a decrease in EM values leads to an increase in the slip ratio response at 0.9 kg, as seen in Figure 9.

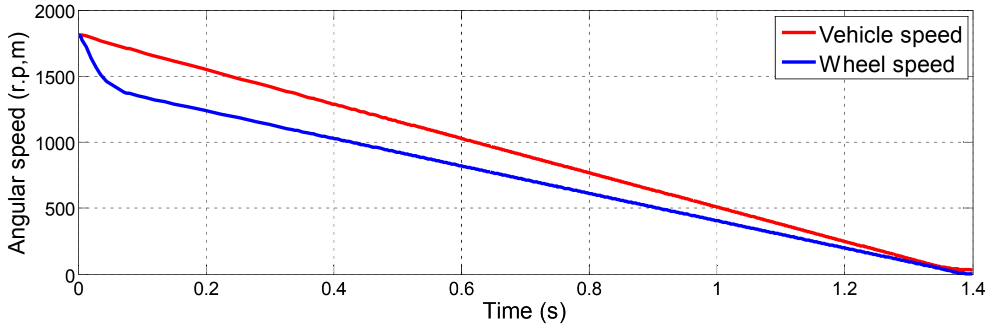
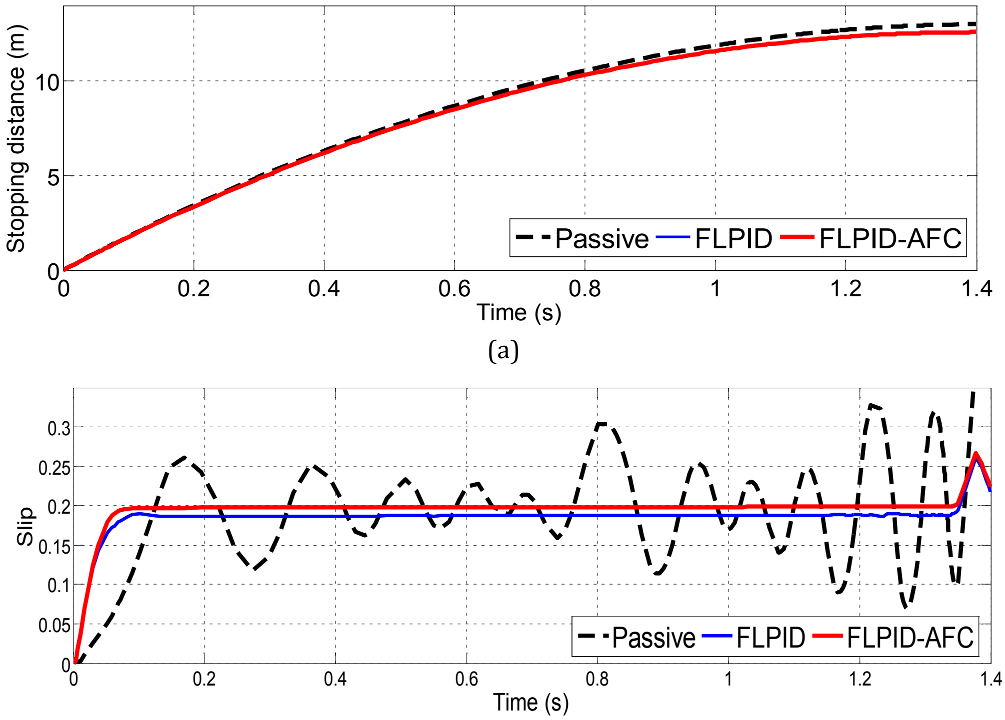


Figure 10. Vehicle vs. wheel speeds during panic braking, FLPID-AFC scheme.

As shown in Figure 10, the affectivity of the AFC technique to the system in order to keep it safe during panic braking. There are potential disruptions that are taken into account that have been absorbed by this technique. From Figure 11(a), displays the stopping distance through three control schemes during the panic braking of the vehicle. Compared with the system under monitoring techniques, the passive control has long stopped by 60 cm. A Slip Ratio, shown in Figure11 (b), illustrates the mechanism's reliability and vehicle moves without yawing from the road, proving that the FLPID with AFC loop is more stable and superior in efficiency than the unstable passive system, as well as the integrated solution with FLPID controller.



(b)

Figure 11. Three control systems during panic braking (ABS) (a) stopping distance and (b) slip ratio.

4. CONCLUSION

To sum up, the FL-PID scheme has been applied to the system and compared with proposed robust technique for speed, stopping distance, and slip ratio control of the anti-lock brake system. The performance of the fuzzy self-tuning PID has been implemented with/without integrating AFC loop in order to test the efficiency of this technique on ABS under dry road condition. Firstly, the incorporation was by tuning the PID control gains with nine fuzzy logic rules, and then implemented it to the system. Secondly, marge the AFC scheme with exists of FLPID in order to prove the effectiveness of this technique. In summary, the system's hold efficiency, robustness, and accuracy have significantly improved, meaning also that vehicle has sufficient stability and steer-ability when panic braking on a dry road.

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