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Experimental Validation of Fuzzy Logic Based Anti-Lock Braking System Used in Quarter Car Model

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Abstract

Many control methods for development of Antilock braking system (ABS) are used. The present study represents the use of Fuzzy Logic in the development of ABS to enhance the control over braking. The purpose of the research is to reduce the accidents due to locking of wheels. Along with this an interdisciplinary approach has increased in automobiles to develop more efficient system. Vehicle dynamics and braking system is complex as they are highly nonlinear and time variant, which causes difficulties in development of conventional ABS. But these difficulties are overcome by Fuzzy logic-based system design that enhances braking performance. To avoid locking of wheel, the wheel acceleration and wheel slip are taken in to consideration. MATLAB SIMULINK environment is used to develop program of fuzzy logic and is interfaced with an experimental setup consisting of ABS implemented in a quarter car model. The membership functions in Fuzzy logic is tuned based on the requirements. The results indicate that fuzzy based ABS control improves the braking performance and the simulation results are validated with experimental setup.

Keywords: *Antilock braking, fuzzy logic, wheel acceleration, wheel slip, quarter car model.*

1. Introduction

In today's technically advanced world ABS is one of the mandatory active safety devices in almost all the vehicles. Generally during the heavy braking, the wheels get locked and steering becomes impossible thereby causing lateral instability. Hence, for the safety of the passengers and to avoid any accidents, it is necessary to have control over the steering and the vehicle has to be stopped at shortest distance. In order to achieve this condition, the vehicle slip value should be maintained low. Many car manufacturers and researchers are working on different algorithms to implement the best intelligent ABS system. But as the problem is nonlinear, and needs expert's judgment based on different conditions such as wheel speed, vehicle speed, road condition etc., and Fuzzy Logic based controller is best opted.

Various methods have been tried to develop an accurate Fuzzy based controller. Radu Emil Precup et al. (2015) used algorithms based on inspiration from nature, namely the simulated annealing and particle swarm optimization for the development of fuzzy logic. Wei-Yen Wang et al. (2012) proposed a robust adaptive control for anti-lock braking system with neuro-fuzzy model. Mehdi Mirzaei et al. (2012) predicted wheel slip response from nonlinear vehicle dynamics model. Rishabh Bhandari et al. (2011) have developed a system to predict the surface type and an appropriate control algorithm for anti-lock brake system. Andon V. Topalov et al (2011) developed a neuro fuzzy network-based feedback controller. Hossein

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Mirzaeinejad et al. (2010) carried out simulations for different wheel speeds to check out robustness of controller by developing a wheel slip relation between friction coefficient of the road surface and slip ratio. Sudeendra Kumar et al. (2009) developed collision avoidance system using fuzzy logic-based controller. Zhiguo Zhao et al. (2009) developed a fuzzy based system that detects the road surface. Andrei Aksjonov et al. (2018) proposed regenerative anti-lock braking system control method that identifies the road condition using Fuzzy logic. Qi Chen et al. (2018) developed performed research on the structural analysis of ABS for fault diagnosis.

2. Analytical Design

Wheel Slip Ratio

In normal operation the wheels angular velocity and cars velocity will be same and slip is given by

$$\text{Slip ratio '}\lambda\text{'} = \frac{\text{V car} - \text{V wheel } (r1\omega1)}{\text{V car}} \text{............ (1)}$$

Where, 'r_1'is wheel, 'ω_1'angular speed of wheel

a) "0%" indicates free rolling of wheel.

b) “100%” indicates tyre locked and the wheels are skidding and vehicle is not stable.

c) Point of optimum brake effect is between these two extremes.

Frictional coefficient as a function of wheel slip is give as; Rishabh Bhandari et al. (2012)

$$\mu(\lambda)=(C_1*(1-e^{-C2\lambda})-C_3\lambda \quad \text{...................................... (2)}$$

Where: (C_1) friction curve (Maximum value), (C_2) is friction curve shape (C_3) is difference between the maximum value of friction curve and value when slip ratio is 1. The graphical representation of above equation is shown in Figure-1.

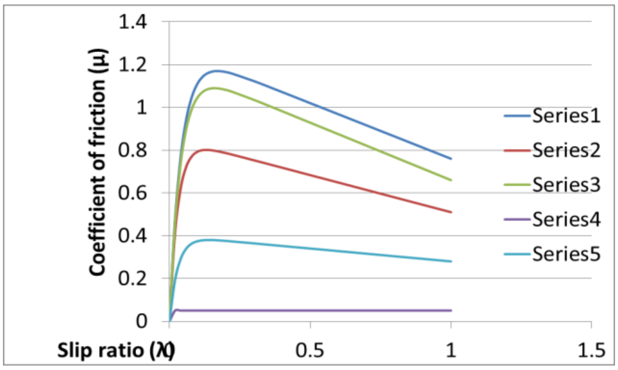

Figure-1. Relationship between braking force and slip ratio for different road surfaces.

Series 1: dry asphalt, Series: 2 for wet asphalt Series: 3 for dry concrete Series: 4 for ice Series: 5 for wet cobalt. It is observed that adhesion coefficient increases with slip up to about 10 to 20% in magnitude depending upon different road conditions.

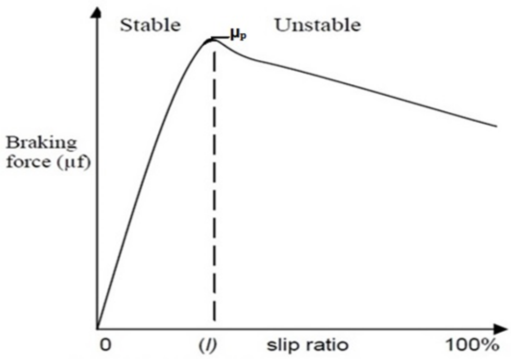

Figure-2 Braking force and slip Relationship

The above graph shown in Figure-2 is divided into two areas: stable and unstable. In the stable zone, balance exists between the braking efforts applied and the adhesion of road surface. In unstable zone when critical slip is passed, no balance exists and wheels will lock, unless the braking force is reduced. Derivation of mathematical model for such a complex system would be a tedious task due to the nonlinear and nondeterministic characteristics of all involved component. Since fuzzy logic is ideally suited to handle non linearity, a fuzzy system was chosen to control ABS.

2.1 Quarter car model

In the Quarter car model, the body pitching, roll, yaw, lateral motions are neglected. The surface texture of road surface along with vertical dynamics are considered in the controller design. Figure -3 shows the braking condition free body diagram of wheel. Mehdi Mirzaei and Hossein Mirzaeinejad (2012).

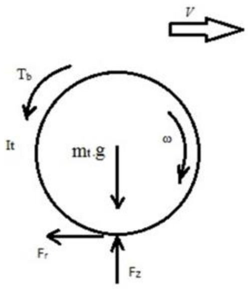

Figure-3 Braking condition free body diagram of wheel

The longitudinal velocity of vehicle V and the angular velocity of wheel ω are obtained as follows [3]

$$\dot{V}=\frac{-Fr}{mt} \qquad (3)$$

$$\dot{\omega}=\frac{1}{It}-(R.Fr-Tb) \qquad (4)$$

The longitudinal force is represented by Fr, mass of quarter car model (total) is indicated by mt , R indicated radius of wheel, It is total moment of inertia of wheel, braking torque is represented by Tb .

On substituting eq. (3) and (4) after differentiating slip ratio equation we get,

$$\frac{d\lambda}{dt} = \frac{-1}{V}\left[\frac{Fr}{mt}(1-\lambda) + \frac{R^2.Fr}{It}\right] + \left(\frac{R.Kb}{V.It}\right)Pb \text{ .... (5)}$$

Eq. (3) and (4) are used in designing simulation model.

2.2 Calculations

To calculate parameters like stopping distance, time required for braking, deceleration of vehicle equations of motion have been taken into account. These parameters are calculated to validate the results of experiments and the result is shown in Table-1.

Table-1. Result for 20km/hr at different road surface condition

Speed (km/hr)	μ	**Stopping Distance (m)**	**Braking Force (N)**	**Stopping Time (Sec)**
20	0.7	3.218	480.2	1.1578
	0.3	17.506	88.29	6.2974

Similarly, for 30km/hr and 40km/hr stopping distance, breaking force and stopping time for different road conditions are calculated and are as shown in following tables.

Table-2. Result for 30km/h at different road surface condition.

Speed	μ	**Stopping Distance (m)**	**Braking Force (N)**	**Stopping Time (Sec)**
30 km/hr	0.8	5.526	627.84	1.326
	0.7	7.225	480.2	1.1578
	0.3	39.296	88.29	9.4348

These values are taken for reference as to compare against experimental values obtained for 30km/h and 35km/h.

2.3 Hydraulic Braking System

As a quarter car model is selected force are calculated for a single wheel. After the application of brake force at pedal it is available at master cylinder. The brake system of Alto vehicle of Maruti Suzuki car is used in the experimental set-up. Standard dimensions are given below which are considered to calculate braking force at different stages.

Master cylinder diameter (d_1) = 19mm

Area of master cylinder =1134.1149 mm^2

Caliper diameter (d_2) = 32mm

Area of caliper = 3216.9908 mm^2 Pedal ratio =4:1

When 1kg of force i.e. 9.81N force is applied at brake pedal then brake force acting on master cylinder is 39.24 N. Force at caliper (clamping force) is calculated as, let F1 be force acting on master cylinder and F_2 be clamping force, then relation between forces is given as

$$\frac{F1}{A1} = \frac{F2}{A2} \quad \text{............} \quad (13)$$

$$\frac{39.24}{1134.1149} = \frac{F2}{3216.9908}$$

$F_2 = 111.3068$ N

Similarly values of clamping force for brake pedal force up to 10kg is shown in Table -3,

Table-3. Force at different location in braking process

Force at Brake Pedal		**Force at Master Cylinder**	**Force Caliper**
kg	**N**	**N**	**N**
1	9.81	39.24	111.3068
2	19.62	78.48	222.6136
3	29.43	117.72	333.9204
4	39.24	156.96	445.2272
5	49.05	196.2	556.5341
6	58.86	235.44	667.8409
7	68.67	274.68	779.1477
8	78.48	313.92	890.4545
9	88.29	353.16	1001.761
10	98.1	392.4	1113.068

This relationship between braking force at brake pedal and braking force at brake disc was necessary to establish for this research work as it is hard to measure braking force at the disc due to large amount of force as compared to force at brake pedal. While force applied at brake pedal can be easily measured by placing load cell on brake pedal. So, by finding the braking force applied at the brake pedal we can find the magnitude of braking force acting on the brake disc.

3. Fuzzy Logic Controller Design

Mamdani FLC is used with two inputs: slip ratio and wheel angular deceleration and one output is force to be applied at brake pedal. Slip, wheel deceleration and the output have five triangular MFs namely VS, S, M, L, VL implying Very small, Small, Medium, Large, Very Large. Table-4 indicates the rule base.

Table- 4. Fuzzy Rule Base

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	Slip Ratio	VS	S	M	L	VL
Wheel Deceleration						
VS		VL	VL	L	M	S
S		VL	VL	L	M	S
M		L	L	M	S	S
L		M	M	M	VS	VS
VL		M	M	S	VS	VS

3.1 MATLAB programming

a) The Figure - 3 is of the editor window for Fuzzy Logic in MATLAB. Figure shows input parameters slip ratio and wheel deceleration on left hand side. Central portion shows rule base used, for this work Mamdani system is used to monitor the ABS. The actuator force is represented as triangular membership as Very Small, Small, Medium, Large, and Very Large.

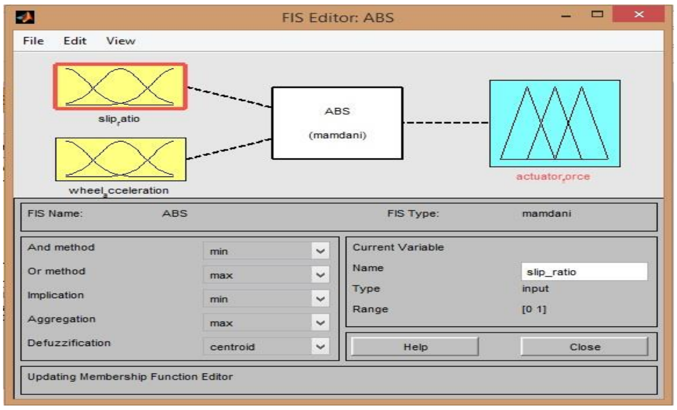

Figure 3. MATLAB system representation

b) Slip ratio is the first output input. As slip ratio varies in between 0 to 1, limits for representation of slip ratio are taken in between 0 to 1. Linguistic variables categorize slip ratio in five sets within the range of 0 to 1 as shown in Figure-4.

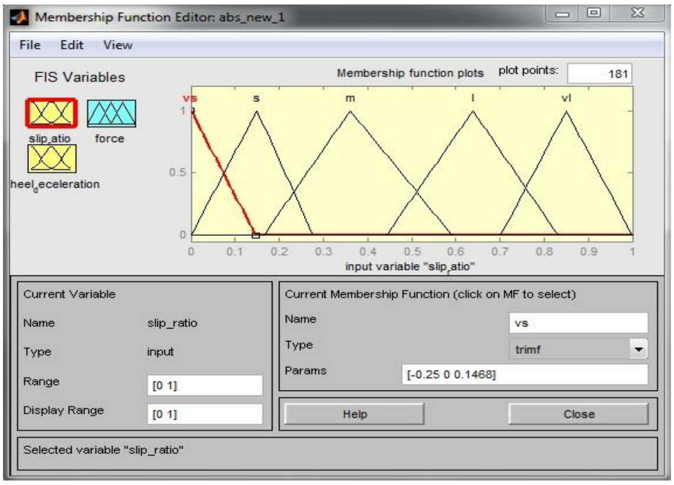

Figure-4. Slip ratio representation in MATLAB

Another input to the fuzzy logic is wheel deceleration. Wheel deceleration is represented with the range of -11 to 0 in five membership function, namely very small, small, medium, large, very large as shown in Figure-5.

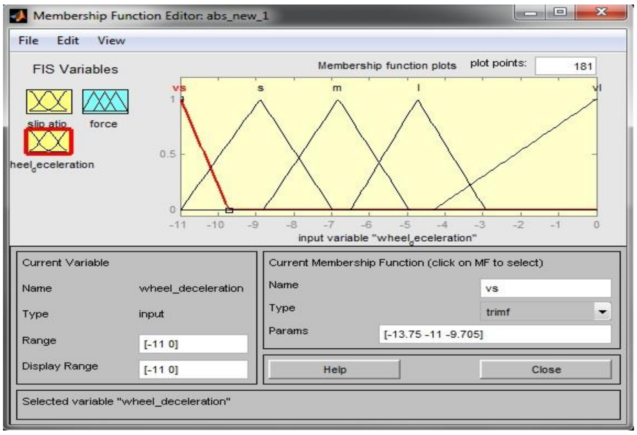

Figure-5. Wheel deceleration in MATLAB

The Braking force that should be applied on the brake pedal is the output of the controller. Limits for this force value are 0 to 10 and is shown in the Figure-6.

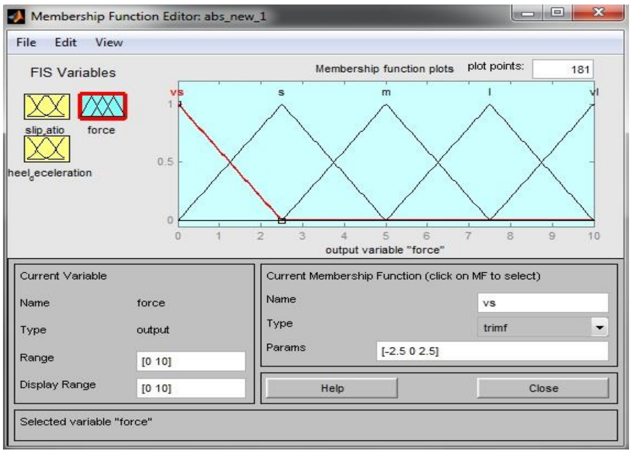

Figure-6. Force representation in MATLAB

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In fuzzy logic initially we define input as well as output. But System is totally incomplete unless and until it has rules defined. In order to define system completely 25 rules have been defined as shown in Figure-7.

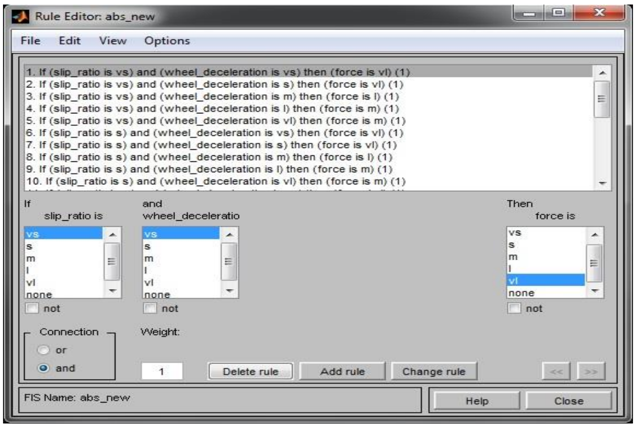

Figure-7. Rules representation in MATLAB

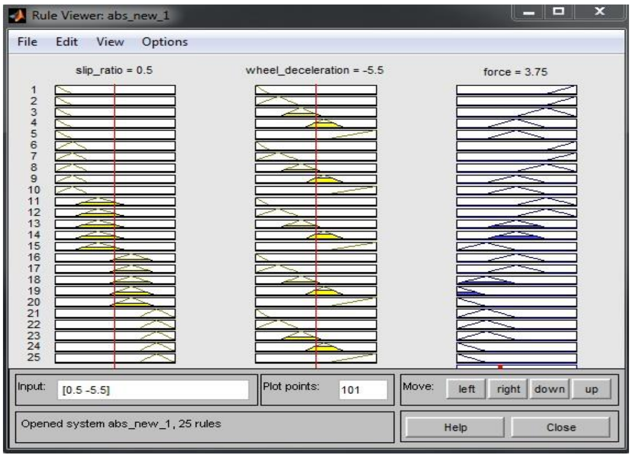

Figure-8. Rule Viewer

The Figure-9, shows the output window developed by fuzzy logic based on the input, output parameters along with rules.

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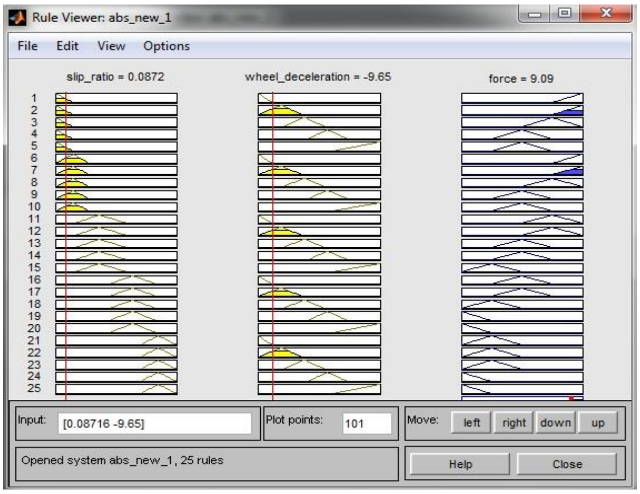

Figure-9. Case 2 representation of Rules

In this case slip ratio is 0.0872 and wheel deceleration is -9.65 so force required to be applied equals to 9.09.

3.2 Simulation

To analyze system simulation model is created using MATLAB-Simulink. Equations (3) and (4) are used to design simulation model. Fuzzy Logic Controller with rule viewer tool from simulink is used in simulation model. The Figure-10 shows the ABS Simulink model for dry road conditions.

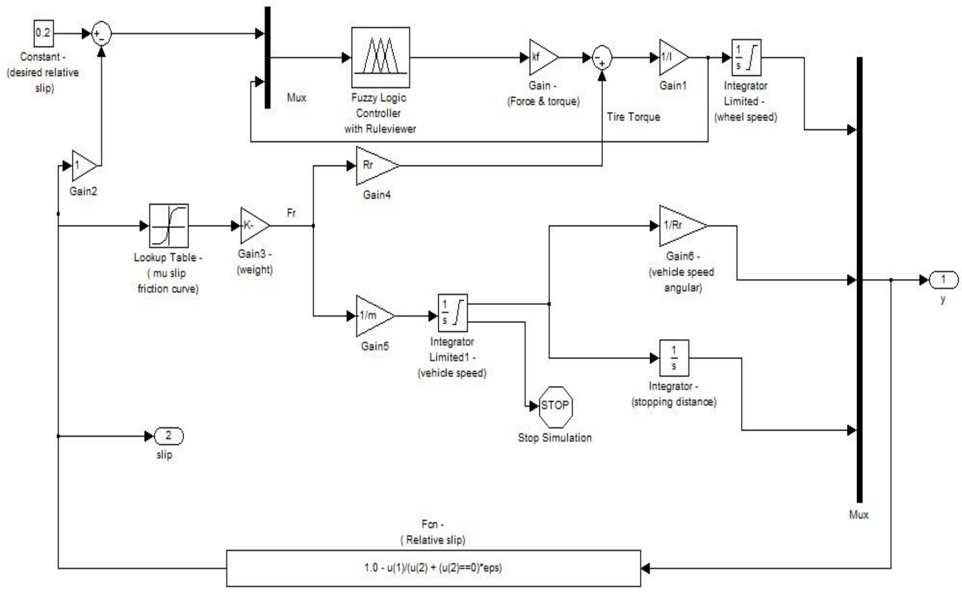

Figure-10. ABS Simulink model for dry road conditions

Slip ratio and wheel deceleration are input to the controller in the model. Based on these input conditions it gives the force required at the wheels. From this force value again wheel deceleration and vehicle deceleration are calculated. From this deceleration velocity and displacements are calculated further. These values are continuously calculated till vehicle and wheel stops. To check it for different road conditions reference slip value is changed an4. d values in lookup table which includes values from slip ratio and adhesion coefficient relation are changed as per the road conditions. Results of simulation for 50km/h are discussed in Results and discussion section. Graph of speed vs time for vehicle angular velocity and wheel angular velocity and graph of slip ratio for a system with Fuzzy ABS and without ABS have been plotted.

4. Experimental Set-up

The experimental setup is shown in Figure-11. There are two rotating wheels a lower wheel and an upper wheel. The lower wheel corresponds to road movement and upper wheel relates to vehicles wheel. Upper wheel drives the lower wheel by friction contact.

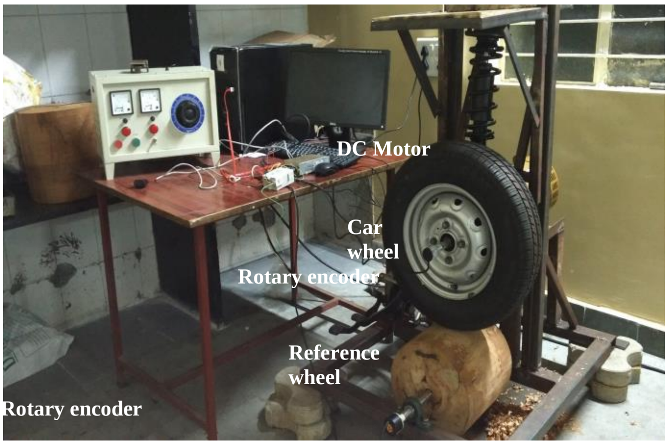

Figure-11. Experimental Setup

On this experimental setup tests were carried out for 30 km/h and 35 km/h. Experimental setup consists of the standard components as shown in Table-5.

Table-5. Bill of Material

Sl.No.	Name	Qty.
1	Alto wheel Assembly (20 Kg)	1
2	Wooden wheel (15 Kg)	1
3	DC Motor (2 HP)	1
4	Rotary Incremental Encoder (1000 ppr)	2
5	Pad Load Cell (0-30 kg)	1
6	Dimmer	1
7	Limit Switch	1

In this setup Alto wheel is attached to the 2 HP motor by using coupler. To this motor dimmer is attached through which speed of wheel can be varied. RPM of DC motor can be varied up to 1500rpm. Wooden wheel is placed below alto wheel which gives us road condition to perform test. Two incremental rotary encoders are attached to the alto wheel and wooden wheel respectively. Through this encoder speed and deceleration of wheels can be measured. Load cell is placed on the brake pedal which shows us the amount of brake force we have applied. To achieve more

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accuracy in calculation of distance travelled limit switch is attached to the brake pedal. When brake pedal is in contact with the limit switch no pulses will be counted and when limit switch looses contact the brake pedal then it will start calculating pulses from which we can calculate stopping distance.

4.1 LabVIEW Programming

LabVIEW is used to read the output given by rotary encoders and load cell. Two rotary incremental encoders are attached to the Programmable Logic Control (PLC). Through this PLC pulses given by the encoders are measured and frequency of these pulses is measured to calculate revolutions per minute (rpm). Through this rpm, angular velocity and angular acceleration is calculated. Limit switch which is connected to brake pedal is also attached to the PLC. Load cell is attached to the NI 6009 module. Output voltage of load cell is in mV so voltage amplifier is used to amplify voltage given by load cell. Slip ratio and wheel deceleration are calculated in LabVIEW. Fuzzy logic which was designed in MATLAB is also developed in same manner in LabVIEW and calculated slip ratio and wheel deceleration are given as input to this fuzzy logic. Fuzzy logic then works on these inputs and gives us the required amount of brake force which is needed to be applied at the brake pedal. Figure-12 shows the programming in LabVIEW for slip ratio

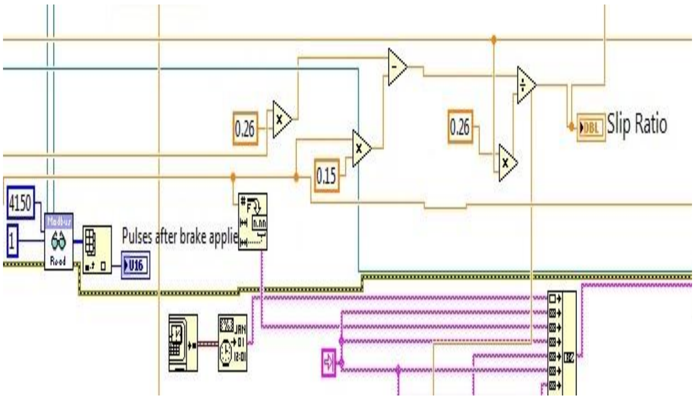

Figure-12. Calculating slip ratio in LabVIEW

Angular velocities calculated for each of wheel are rearranged in such a manner to get slip ratio. Figure-13 shows the calculation of angular acceleration.

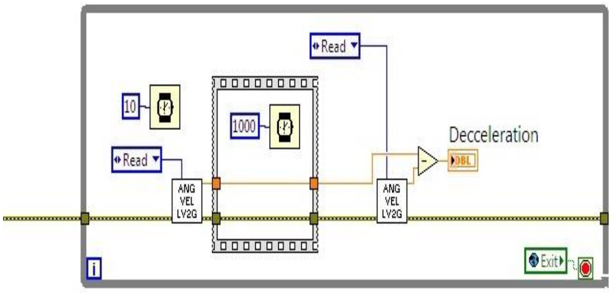

Figure-13. Wheel deceleration calculation in LabVIEW

Difference in between two velocities after the application of brake is measured to calculate wheel deceleration. As both slip ratio and wheel deceleration are needed to be calculated continuously so they are put in While loop. Wheel deceleration is calculated for the Alto wheel. Figure-14, shows the representation of two inputs to Fuzzy Logic Toolbox in LabVIEW,

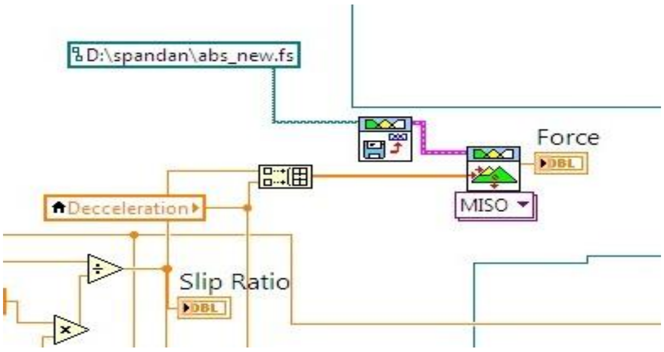

Figure-14. Fuzzy Logic in LabVIEW

As slip ratio and wheel deceleration are the input to the Fuzzy logic, so Multi Input Single Output (MISO) box is chosen. To this box wheel deceleration and slip ratio are given as input and output given by this is Force which is shown on the right side of MISO.

Figure-15, shows the Virtual Interface developed in LabVIEW which shows us all required reading on computer screen.

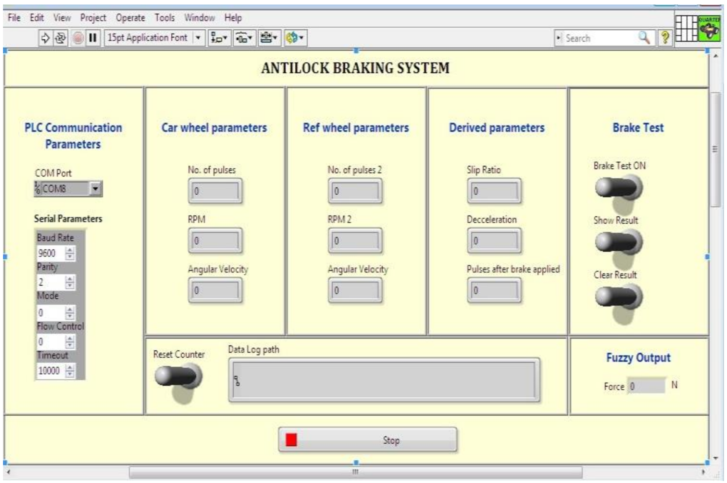

Figure-15. Virtual Interface for ABS

As seen in above figure column first gives us the parameters which are required to establish communication with the PLC. Second column named as the car wheel parameters gives us the output of rotary encoder attached to the Alto car wheel. First block of this column gives us the No. of pulses generated by rotary incremental encoder, second block gives us the RPM and third block gives us the angular velocity of encoder attached to the car wheel. Same parameters which are shown in second column are shown in third column for the reference wheel. Fourth column gives us the derived parameters which are the required output. This column gives us Slip ratio and wheel deceleration. Third block of this fourth column gives us the pulses after brakes applied as this block is connected to the limit switch. From this block we can calculate stopping distance. Fifth column gives us the knobs which are required while performing brake test. Below this fifth column there is block which is brake force, output of the Fuzzy Logic and this much amount of force is required to be applied at the brake pedal.

4.2 Result and Discussion

Simulation results

Input parameters given in MATLAB command window are as follow;

Vehicle velocity 50 km/hr (13.88 m/s)

Radius of wheel 0.260 m

Acceleration due to gravity 9.81 m/s2

Slip = (0:.05:1.0);

μ = [0 .8546 1.11 1.163 1.165 1.1463 1.123 1.09 1.072 1.046 1.02 0.994 0.968 0.942 0.916 0.89 0.864 0.8381 0.8121 0.7861 0.7601];

Following are the results obtained:

a) **Relationship between the vehicle and wheel angular velocity with Fuzzy ABS:**

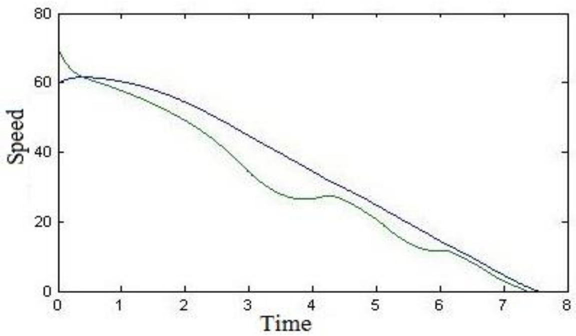

Figure-16. Vehicle and wheel angular velocity with Fuzzy ABS

In Figure-16, the upper line represents the vehicle angular velocity and lower line represents the wheel angular velocity. Figure-16 shows that wheel and vehicle stop with same time. Wheel angular velocity line is not as linear as vehicle angular velocity. As there is continuous change in brake force applied to avoid the locking of brakes there is variation for angular velocity.

b) **Relationship between the vehicle and wheel angular velocity without Fuzzy ABS:**

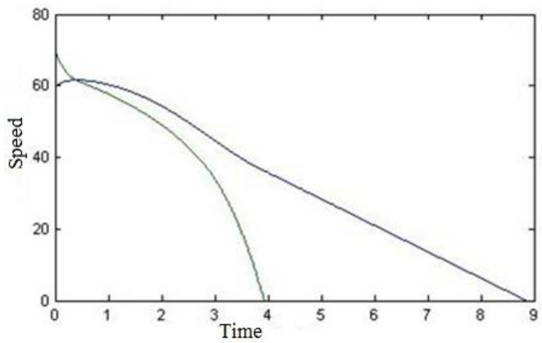

Figure-17. Vehicle and wheel angular velocity without ABS

In Figure-17 the wheel angular velocity reaches to zero at near about 4 seconds and vehicle angular velocity becomes zero near 9 seconds. So, in this condition wheels are locked and vehicle tends to move along the path which is a case of instability. In this case driver does not have control on vehicle during the course of braking. It is also confirmed from the diagram that there is increase in braking distance.

c) Slip ratio for Fuzzy based ABS

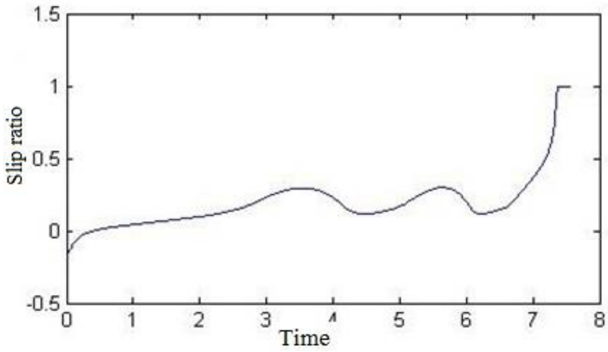

Figure-18. Slip ratio for Fuzzy based ABS

From the Figure-19 it is seen that slip ratio has not gone beyond the prescribed value. This is one of the important parameters in controlling the vehicle.

d) Slip ratio for Fuzzy based ABS

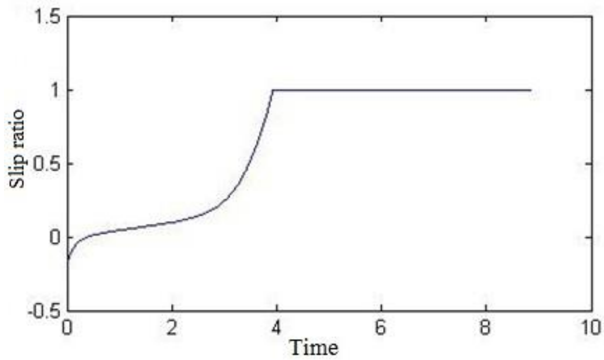

Figure-19. Slip ratio for system without ABS

From Figure-19, it is seen that wheel slip ratio reaches to value of 1 at 4 seconds implying that wheels are locked at this condition, which is unwanted situation while driving.

4.3 Experimental results

Implementation of Fuzzy ABS has been carried out on quarter car model. Number of real time experiments has been performed and results are compared with analytical results. To imitate the behavior of the vehicle during braking on a dry and straight road wheel is accelerated until the velocity of wheel reaches 30km/h and 35km/h. It should be noted that on the available setup experiments can be performed for specific road condition i.e. for dry conditions only. The stopping distance is calculated by rotating the wheel at a speed of 30km/hr and panic braking is applied. Under panic braking the wheel decelerates and stops. The reduction in wheel speed is captured by rotary encoder and is recorded in Excel sheet with respect to time period and the system calculates angular velocity and stopping time. A sample sheet is as shown in Table-4.

DATE	TIME	ANGULAR VELOCITY
1/26/2020	7:02:20 AM	31.834806
1/26/2020	7:02:20 AM	31.834806
1/26/2020	7:02:21 AM	31.834806
1/26/2020	7:02:21 AM	31.834806
1/26/2020	7:02:21 AM	31.834806
1/26/2020	7:02:22 AM	29.530971
1/26/2020	7:02:22 AM	29.530971
1/26/2020	7:02:23 AM	9.434581
1/26/2020	7:02:23 AM	9.434581
1/26/2020	7:02:23 AM	0.000000
1/26/2020	7:02:24 AM	0.000000
1/26/2020	7:02:24 AM	0.000000
1/26/2020	7:02:24 AM	0.000000
1/26/2020	7:02:24 AM	0.000000

From the tabulated value the number of revolutions observed till wheel stops completely is calculated as (n) = 3.826. The stopping distance is calculated as follows:

Distance travelled before stopping (S) = $2*\pi*r*n=2*\pi*0.260*3.826 = 6.3503$ m

The experiment is repeated number of times to find the repeatability of the results. The Mean stopping distance was observed to be 6.1205 m, Standard Deviation of 0.163077 m and the Standard Deviation of the Mean (SDM) is 0.06657. As the SDM is very close to 0 there is no much variations in the results obtained from number of trials. The procedure is repeated for 35 km/hr and the mean stopping distance is found to be 7.969 m with good repeatability. The comparative results for stopping distance by Simulation and Experimentation is shown in Table-4.

Results for 30km/h and 35 km/h are shown in Table-4.

Table-4. Estimation of Simulation and Experimental Stopping Distance for different speeds

Speed km/h	Stopping Distance (m)	
	Simulation	Experimental
30	5.5260	6.1205
35	7.527	7.969

A 10.21% of variation in stopping distance is observed between the simulation result and experimental result for speed of 30 km/hr and 5.70 % is observed in case of 35 km/hr. A small amount of variation in stopping distance is observed between the simulation and experimental result for both 30km/h and 35km/h due to the human interference in braking process during the experimentation.

5. Conclusion

For a system like Antilock Braking system it is hard to develop the mathematical model to accurate level as there are highly nonlinear relationship between the parameters, hence the Fuzzy Logic, linguistic variables come into picture, to make system reliable and useful to the great extent. To develop such systems, experience of engineering expertise is required. A linear relation developed by using fuzzy logic helps us with easily dealing with this nonlinear system. From graph obtained from simulation of Speed vs. Time it is seen that with the use of FLC ABS there is decrease in time for bringing wheel and vehicle to stop by 1.2 sec. From results of slip ratio, it can be seen that by use of FLC slip ratio is remained always within controlled limit hence can overcome complex nonlinear behavior of system. There is human interference in braking process as observer has to see the value of force to be applied and have to apply it at brake pedal so a marginal increase in stopping distance as well as in stopping time is observed. There is a small difference of 5% to 10% for speed of 30km/h and 35km/h in stopping distance between the simulation and experimentation result due to human intervene during the braking and calculation of stopping distance. However, this can be eliminated by having fully automated system. The convincing advantage of fuzzy logic is the ability to modify and tune certain parts of this characteristic surface easily and carefully. While soft computing methods like Fuzzy control, doesn't need a precise model. This method can be easily extended, however to claim the validity of FLC more sampling data regarding slip and force have to be collected and analyzed.

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