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APPLICATION OF THE HYBRID BOND GRAPHS AND FUZZY CONTROL ON ANTI LOCK BRAKING SYSTEM SLIDING MODE

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ABSTRACT: This paper presents application of the fuzzy control and hybrid bond graphs modeling and simulation of anti-lock braking system using Dymola. It is shown on this practical example that the use of Dymola software package will simplify the modeling and simulation. The proposed approach is verified through digital simulation and experimental results showing good system characteristics. The results obtained by the bond graph modeling are presented in this paper.
Keywords: Hybrid bond graph, Fuzzy control, ABS - anti lock braking system, simulations

1. SYSTEM DESCRIPTION

ABS (anti-lock brake system) a hydraulically-powered mechanism which prevents the wheels from locking during braking, thus shortening the stopping distance and allows full manageability car when braking.

In order to prevent abruptly stopping of vehicle, an anti-lock braking system (ABS) is used in most modern vehicles. It also reduces stopping distances on slippery road surfaces by limiting wheel slip and minimizing lockup, since rolling wheels have much more traction than locked ones. The processor is processed boot informations independent for every wheel and precisely calculates the value of the number of the revolution and slip.

In moment antecedent the wheels is locked by control and sensor. Along the sensor and electromagnetic construction the pressure of the oil in brake's cylinder is lower. The torque moment of the brake is lower and wheels can normal gyration. In that moment sensors is activated electromagnetic throttle in counteract, the pressure of the oil and brake intensity is again bigger of the bounded of the wheels and cycles are again in the beginning.

This hange of the pressure are very quickly because there are used electromagnetic control throttle. The pressure changes are very quickly (about 3-5 times in second). The mechanism is iterate enough quickly so that wheels is always nearly of the brake limits, so that efficiency is bigger and can't be attain. All process is independent of the driver, the information about system arrive to him as vibrate of the brake's shoe.

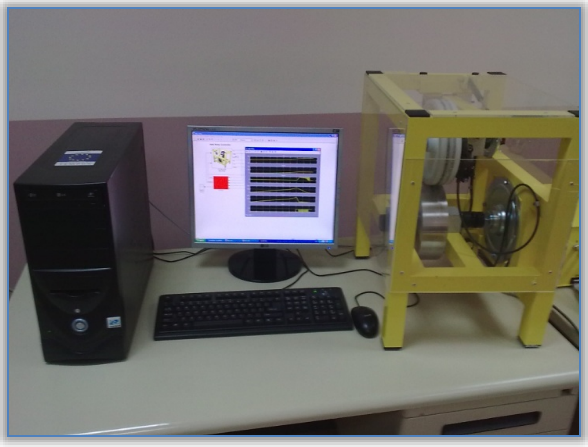

Figure 1: ABS experimental framework (Inteco)

The anti-lock bracking system (ABS) in cars were implemented in he late 70's. ABS are designed to optimize braking effectiveness while main car contrallability. In this work we will described prototipe of the ABS brake system made by INTECO, Figure 1 (Inteco, 2008).
There is considered only longituionlal motion and demontrated in lab model by simulation for various road condition (wet asphalt) and transition between such conditions (for emergency break ing occurs and the road switches from dry to wet or vice versa).
ABS is driven by the powerful, flat DC motor. There are three identical encoders measuring the rotational angles of the wheels and the deviation angle of the alance lever of the car wheel. The power interface amplifies the control signals which are transmitted from the PC to the DC motor. It consists of two rolling wheels. The lower vehicle-road wheel represents vehicle motion and it has smooth surface which can be covered by desired material in order to animate different road surface. The upper wheel models the vehicle wheel and it permanently remains in a rolling contact with the lower wheel, as it is the case with the real world situation. This wheel is in connection with the balance lever and it is equipped in a tire.
At the beginning of an experiment the wheel animating the relative car-road motion is accelerated to a given threshold velocity. The wheel accelerats following two rotational motion of the car road wheel. The DC drive is switched off to enable free motion of both wheels. It consists of two rolling wheels. The lower vehicle-road wheel represents vehicle motion and it has smooth surface which can be covered by desired material in order to animate different road surface. The upper wheel models the vehicle wheel and it permanently remains in a rolling contact with the lower wheel, as it is the case with the real world situation. This wheel is in connection with the balance lever and it is equipped in a tire.
To understand the braking process one has to know relations between the vehicle tire and road during braking. The objective of ABS is to control wheel slip to maximize the coefficient of friction between the tire and road for any given road surface while the car is controllable.
If this wheel becomes motionless, it means that it remains in slip motion -the car velocity is not equal to zero or is absolutely stopped, the car velocity is equal to zero. In the first case the ABS algorithm has to unlock the wheel to stop its slipping. The wheel starts to rotate and after a short time period it is stopped again. This process is repeated as long as the car velocity achieves zero value (the wheel animating the road motion related to car is stopped). If the braking time period is too long the wheel remains locked in slip motion and the car starts an uncontrollable motion. If this period is too short the wheel remains to long in the rolling stage and the brake distance is also enlarged.

2. MATHEMATICAL AND BOND GRAPH MODEL

An ABS graphical model is shown in Figure 2. The considered laboratory model has two rolling wheels: the lower wheel animates relative road motion and the upper wheel is car permanently remaining in a rolling contact with the lower wheel. Despite this model simplification, it preserves the fundamental characteristics of real system. Car vehicle is the product of angular vehicle of the under wheel and it's radius, while the angular car's velocities is the product of the angular velocity of the upper wheel. According to Figure 2 there are three torques acting on the upper wheel: the braking torque M1, the friction torque in the upper bearing and the friction torque among the wheels, as well as two torques acting on the lower wheel - the friction torques in the lower bearing and among the wheels. Besides, two more forces are present on the lower wheel: the gravity force of the upper wheel and the pressing force of the shock absorber.

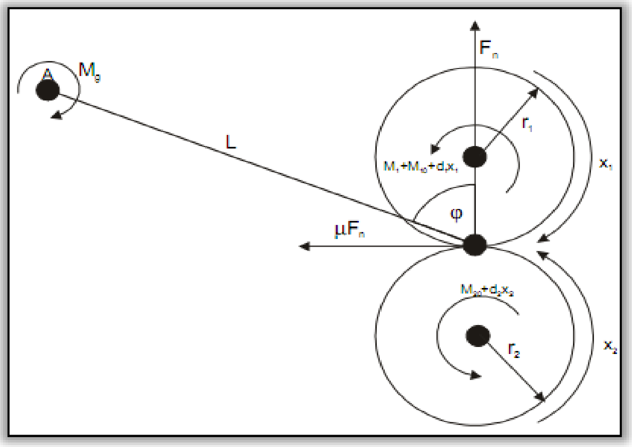

Figure 2: ABS graphical model

The friction force is proportional to the normal pressing force is the proportional coefficient $F_n\mu(\lambda)$. The following equations are used:

$$\begin{gathered} s=\operatorname{sgn}(r_2x_2-r_1x_1) \\ s_1=\operatorname{sgn}(x_1) \\ s_2=\operatorname{sgn}(x_2) \end{gathered} \tag{1}$$

Using the Newton's second law, the upper wheel dynamics is described as:

$$J_1\dot{x}_1=F_n r_1 s\mu(\lambda)-d_1x_1-s_1M_{10}-s_1M_1 \tag{2}$$

where: J_1 is the moment of inertia, d_1 is the viscous friction coefficient and M_{10} is the static friction of upper wheel, $\mu(\lambda)$ is the coefficient of proportion called the road adhesion coefficient. In a similarly manner, the motion of lower wheel can be defined as:

$$J_2\dot{x}_2=-F_n r_2 s\mu(\lambda)-d_2x_2-s_2M_{20} \tag{3}$$

where J_2 is the moment of inertia, d_2 is the viscous friction coefficient and M_{20} is the static friction of the lower wheel.

The next marks are used in bond graph modeling:

- 0-is a zero-junction (0-junction). Each of the power bonds connected to a zero junction have equal effort terms. The flow terms of the power-bonds connected to the zero junction sum to zero, i.e., $flow_{in}-flow_{out}=0$.
- 1-is a one-junction (1-junction). The power bonds connected to a one junction have equal flow terms. The effort terms of the power-bonds connected to the one junction sum to zero, i.e., $effort_{in}-effort_{out}=0$.
- mR - Bond graphic modulated resistor is a modulated passive One Port element. It inherits the effort and flow variables as well as the modulating signal from the modulated passive OnePort. The resistance is modeled as a real-valued variable the causality of the resistor is free.
- mTF-The bond graphic modulated transformer element. It inherets the effort and flow variables from the modulated direct TwoPort. The transformation constant is modeled as a real-valued variable. The constatnt is defined as the amplification of flow from the inflow to the outflow. Some other bond graph references define the transformation constant as amplification of effort from the inflow to the outflow. The transformer model has one causality stroke.
- mGY-The bond graphic modulated gyrator element. The bond graphic modulated gyrator is a modulated direct Two Port element It inherits the effort and flow variables from the modulated directed TwoPort. The gyrator constant is modeled as a real valued variable. The bond graph literature is not constant in the definition of the gyration constant. In this library the constant is is defined as the amplification of flow at the inflow to effort at the outflow. Some other bond graph references define the gyration constant as the amplification of effort at the inflow to the flow at the outflow. The gyrator has zero or two strokes
- mSf- The modulated flow source is a modulated active OnePort element. It inherits the effort and flow variables from the modulated active OnePort The modulated flow to be generated is modeled as a real-valued variables. The flow source has its causality stroke at the source.
- I-The bond graphic linear inductor element. The bond graphic linear inductor is a passive OnePort element. It inherits the effort and the flow variables from the passive OnePort. The inductance is modeled as a parameter. The inductor model has a preferred causality at the element.

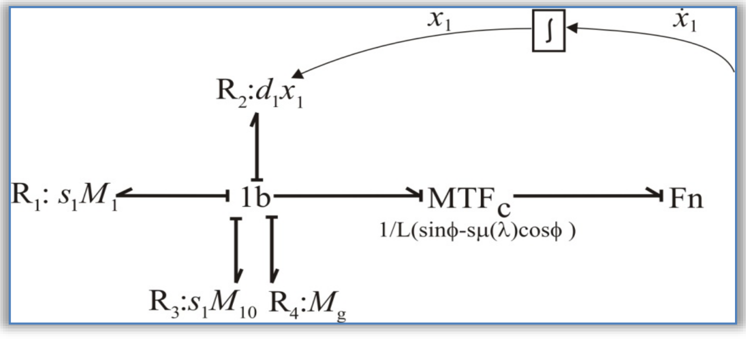

Figure 3: Bond graph model of the normal force

The normal force F_n can be derived from the sum of torques in the point A (Figure 3) as:

$$F_n=\frac{M_g+s_1M_1+s_1M_{10}+d_1x_1}{L\left(\sin\varphi-s\mu(\lambda)\cos\varphi\right)} \tag{4}$$

The dynamic of the ABS models is definite with equations (4) and (5):

$$J_1\dot{x}_1=F_n r_1 s\mu(\lambda)-d_1x_1-s_1M_{10}-s_1M_1 \tag{5}$$

The flow detectors (D_f) connected to velocity points in the inertial frame are not present in the actual system,i.e., the actual system is not instrumented with an inertial sensor. These flow detectors are simply added to plot the x and y positions of the vehicle centre of mass in the inertial frame and also to modulate the modulated transformer elements in the part of the junction structure.

$$J_1\dot{x}_1 = \frac{M_g + s_1 M_1 + s_1 M_{10} + d_1 x_1}{L(\sin\varphi - s\mu(\lambda)\cos\varphi)} r_1 s\mu(\lambda) - s_1 M_1 - d_1 x_1 - s_1 M_{10} \quad (6)$$

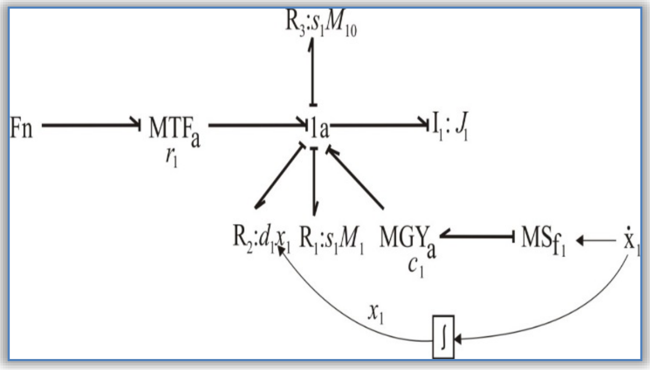

Figure 4: Bond graph schema of the wheel vehicle model

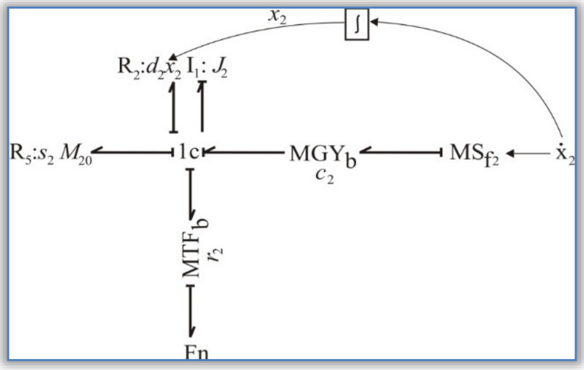

Figure 5: Bond graph model of the road wheel

$$J_2\dot{x}_2 = -F_n r_2 s\mu(\lambda) - d_2 x_2 - s_2 M_{20} \quad (7)$$

$$J_2\dot{x}_2 = \frac{M_g + s_1 M_1 + s_1 M_{10} + d_1 x_1}{L(\sin\varphi - s\mu(\lambda)\cos\varphi)} r_2 s\mu(\lambda) - d_2 x_2 - s_2 M_{20} \quad (8)$$

Were: x_1 is angular velocities of the upper wheel, x_2 is angular velocities of the under wheel, r_1 i r_2 are radiuses of the wheels, respektivno. The torque moments J_1 and J_2, d_1 and d_2 are the coefficient of the viskozity friction, M_{10} and M_{20} are statistic friction, upper and under wheels. Were M_g is gravitational and shok absorber torque acting on the balance lever, L distance between the contact point of the wheels and the rotational axis og the balance lever, φ is angle between the normal in the contact point and the line L.

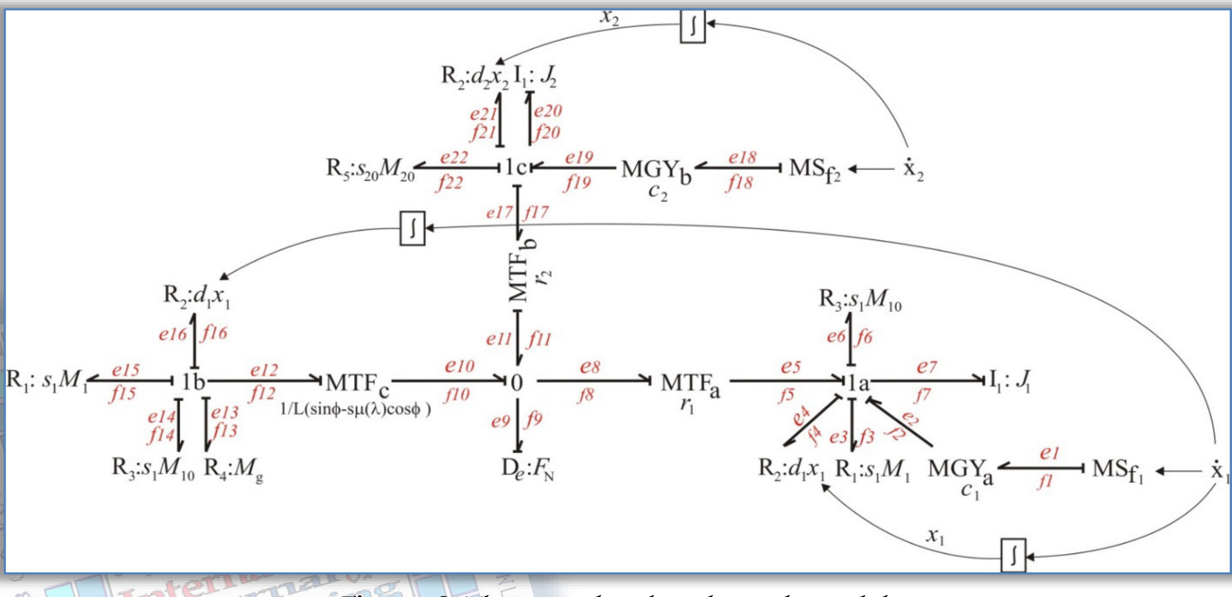

Figure 6: The complete bond graph model

Corresponding bond graph used for simulation is given in Dymola in follow picture (Figure 7).

The controlled variable is the wheel slip, so that it is of great importance to describe its dynamics in a proper manner. In normal operating conditions, the angular velocity of wheel would match the forward angular velocity of vehicle. During the braking and acceleration phases these velocities differs one from other, and their difference is called the wheel slip λ, and it is generally defined by:

$$\lambda = \begin{cases} \dfrac{r_2x_2 - r_1x_1}{r_2x_2}, r_2x_2 \geq r_1x_1, x_1 \geq 0, x_2 \geq 0, \\ \dfrac{r_1x_1 - r_2x_2}{r_1x_1}, r_2x_2 < r_1x_1, x_1 \geq 0, x_2 \geq 0, \\ \dfrac{r_2x_2 - r_1x_1}{r_2x_2}, r_2x_2 < r_1x_1, x_1 < 0, x_2 < 0, \\ \dfrac{r_1x_1 - r_2x_2}{r_1x_1}, r_2x_2 \geq r_1x_1, x_1 < 0, x_2 < 0, \\ 1, x_1 < 0, x_2 \geq 0, \\ 1, x_1 \geq 0, x_2 < 0. \end{cases} \tag{9}$$

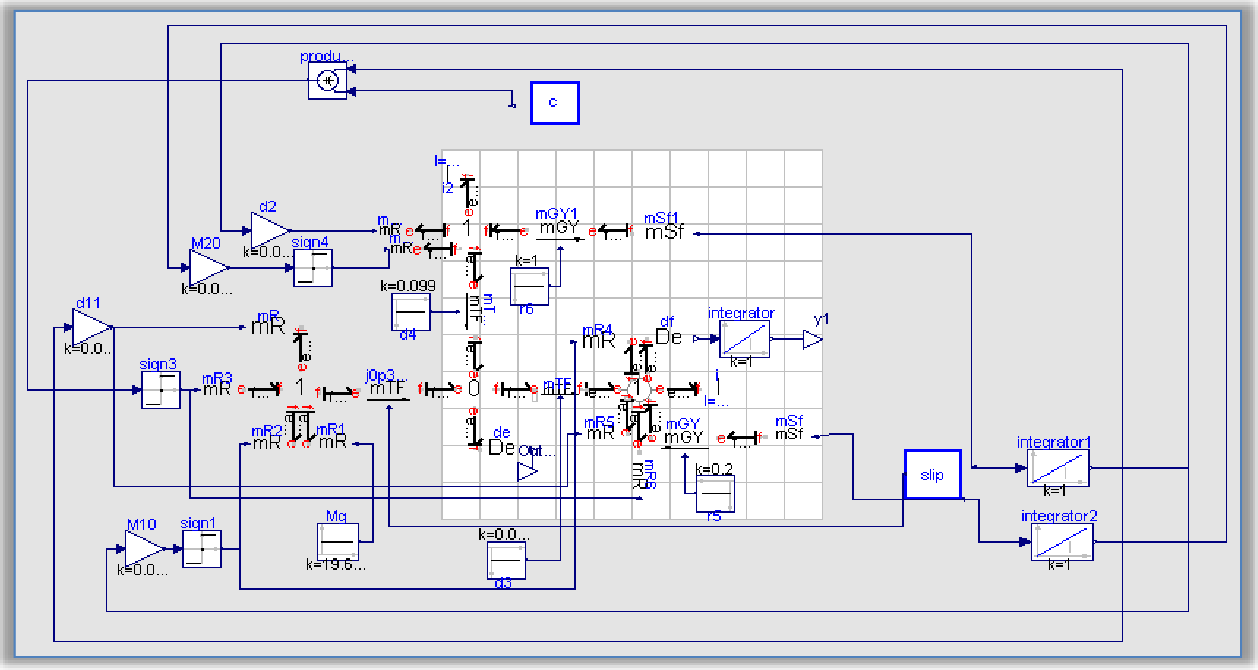

Figure 7: Completely bond graph model of ABS system in Dymola

Corresponding switch function in Dymola is given in Figure 8:

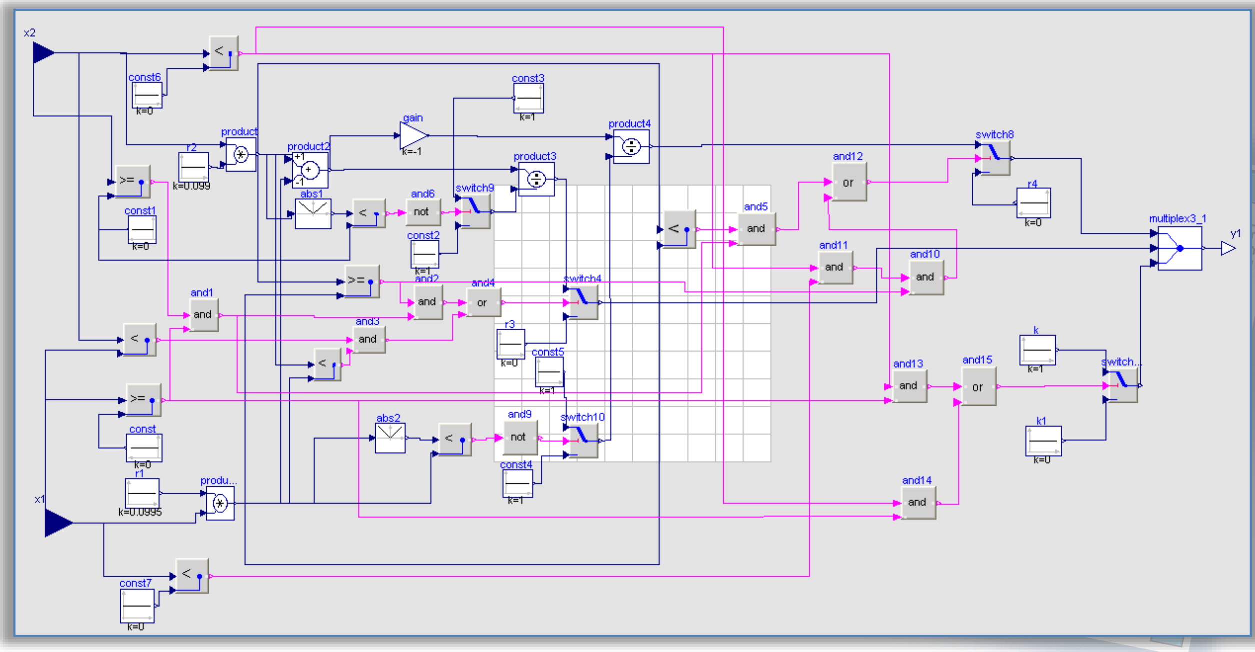

Figure 8. Function of lambda in Dymola

For all quarter vehicle model operating conditions a zero value of wheel slip means that wheel and vehicle velocities are equal, and when the wheel slip is equal to one vehicle wheel is not rotating anymore and skidding on the road surface, i.e., vehicle is no longer steerable.

The road adhesion coefficient μ(λ) is nonlinear function of wheel slip and other physical variables, and one of its models can be defined by the following equation:

$$\mu(\lambda)=\frac{w_4\lambda^p}{a+\lambda^p}+w_3\lambda^3+w_2\lambda^2+w_1\lambda \qquad (10)$$

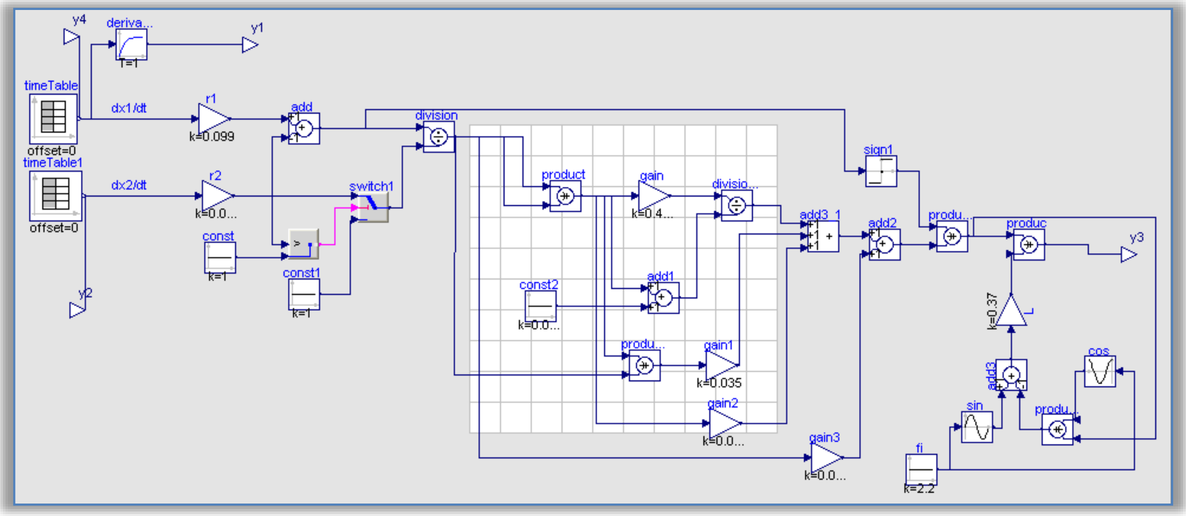

Figure 9: Subfunction slip with functional velocities of wheel and road

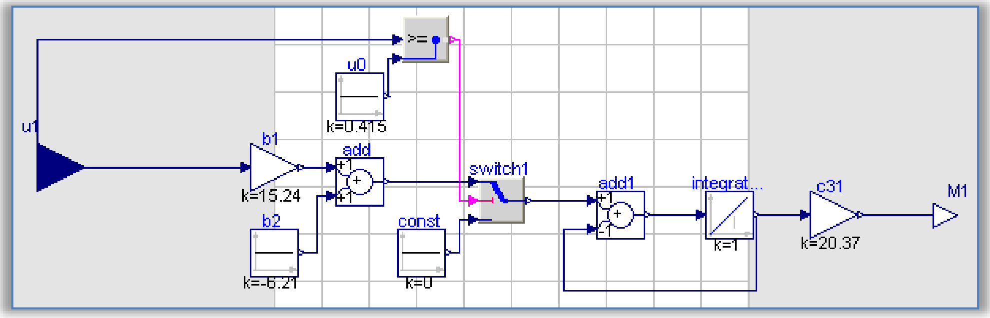

Figure 10: Blocks of subfunctions M1

The simulation results are showen in follow pictures:

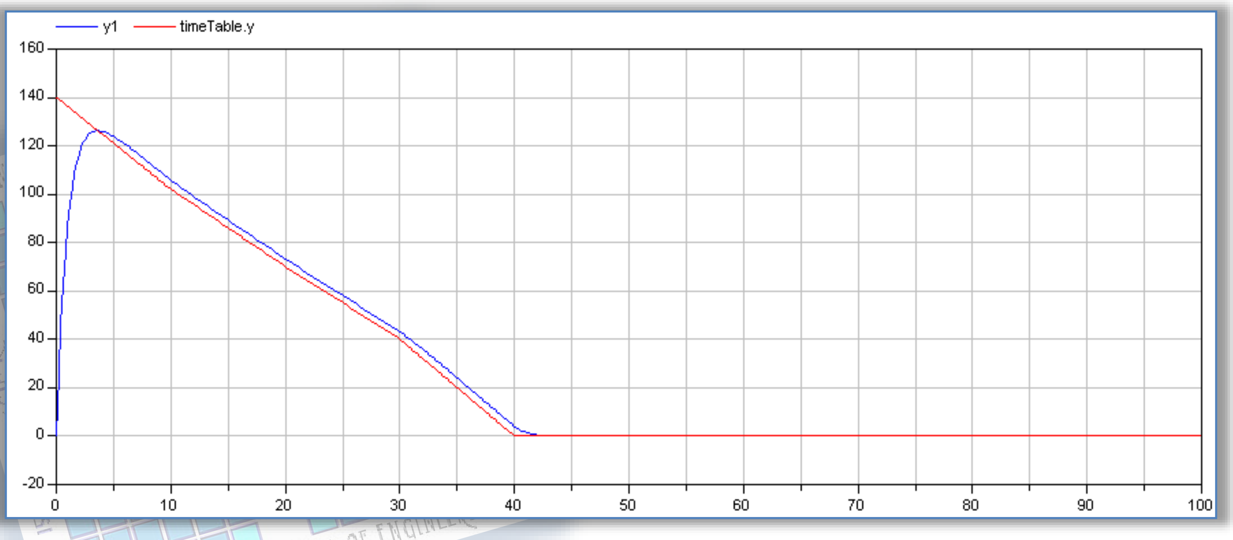

Figure 11: Wheel velocity (red line) and acceleration (blue line)

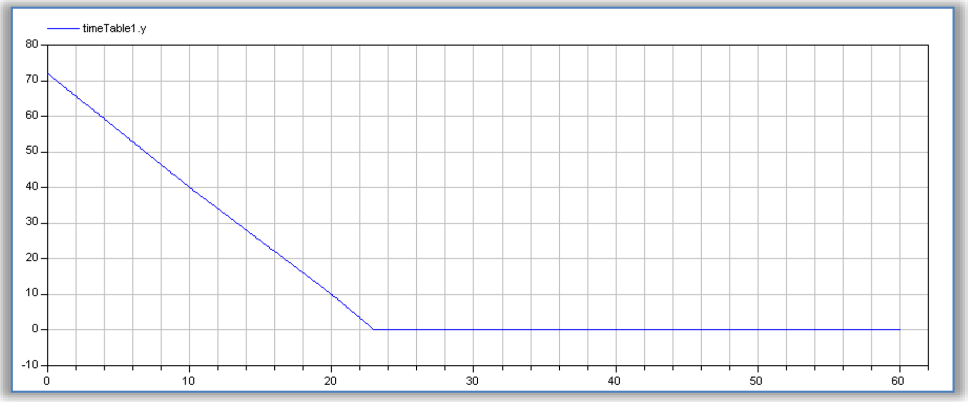

Figure 12: The road velocity

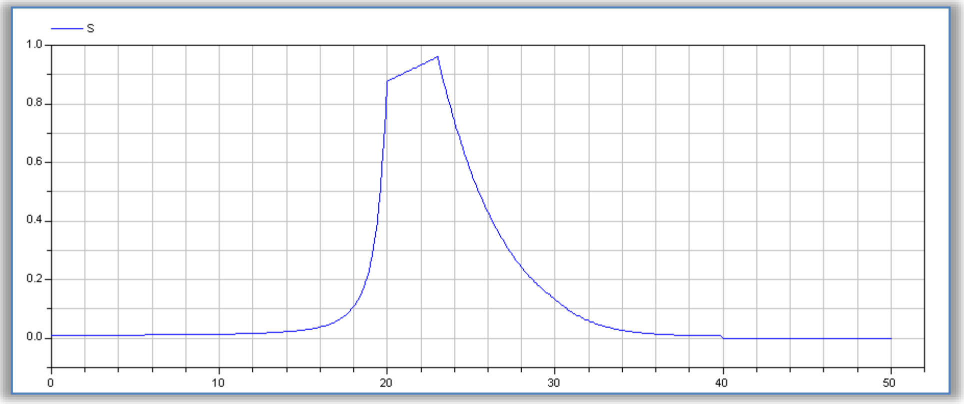

Figure 13: Function of slip friction curves in function of time for asphalt dry road condition for different vehicle speeds

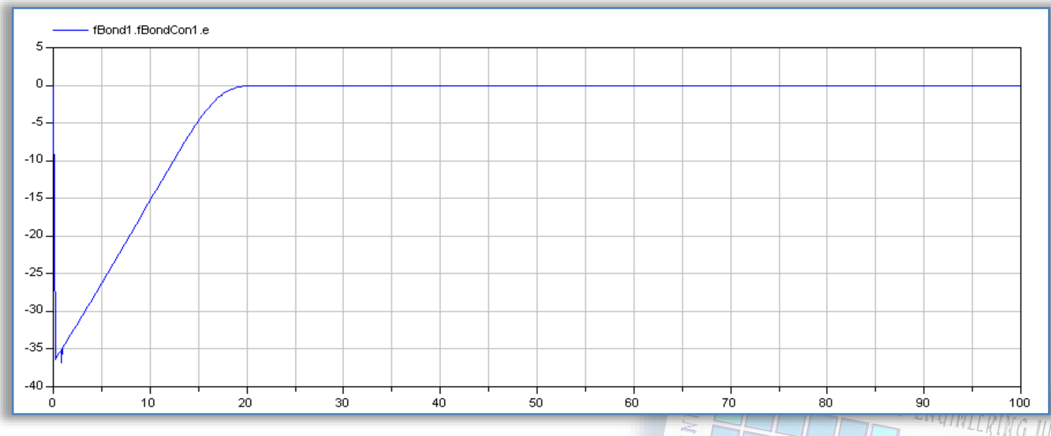

Figure 14: Longitudinal force without ABS

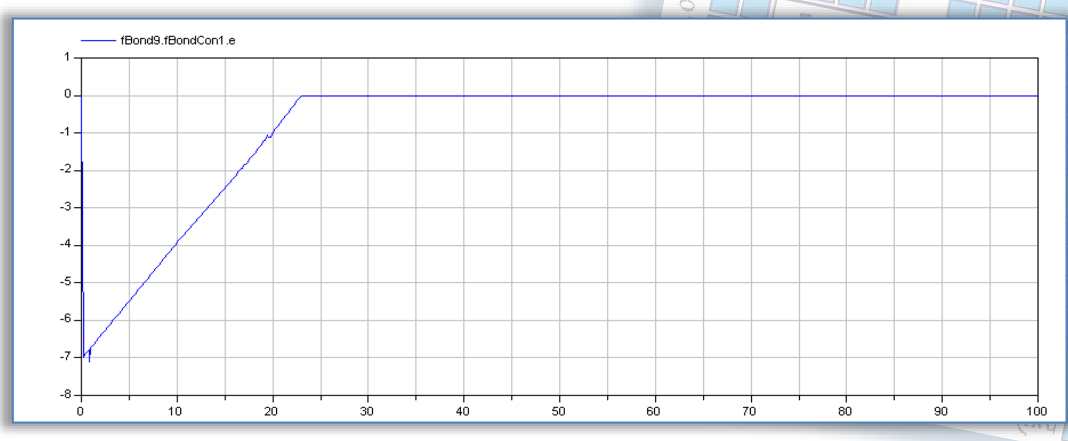

Figure 15: Normal force without ABS

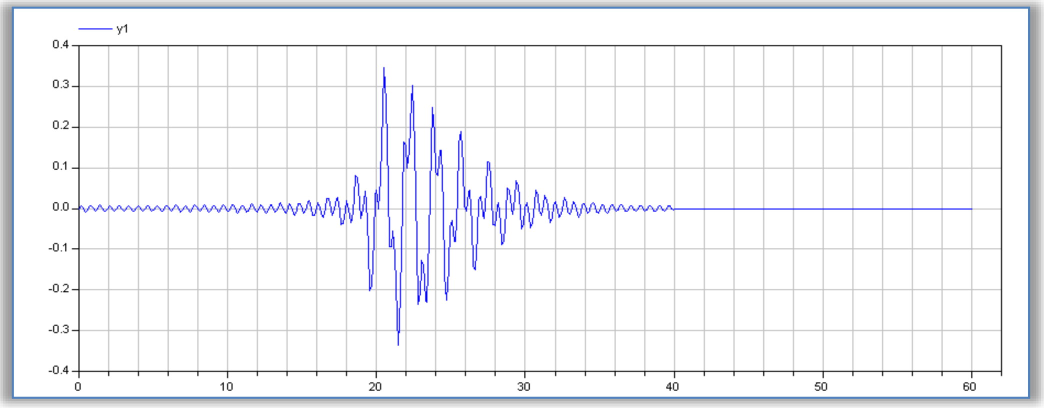

Figure 16: Function μ in function of the time

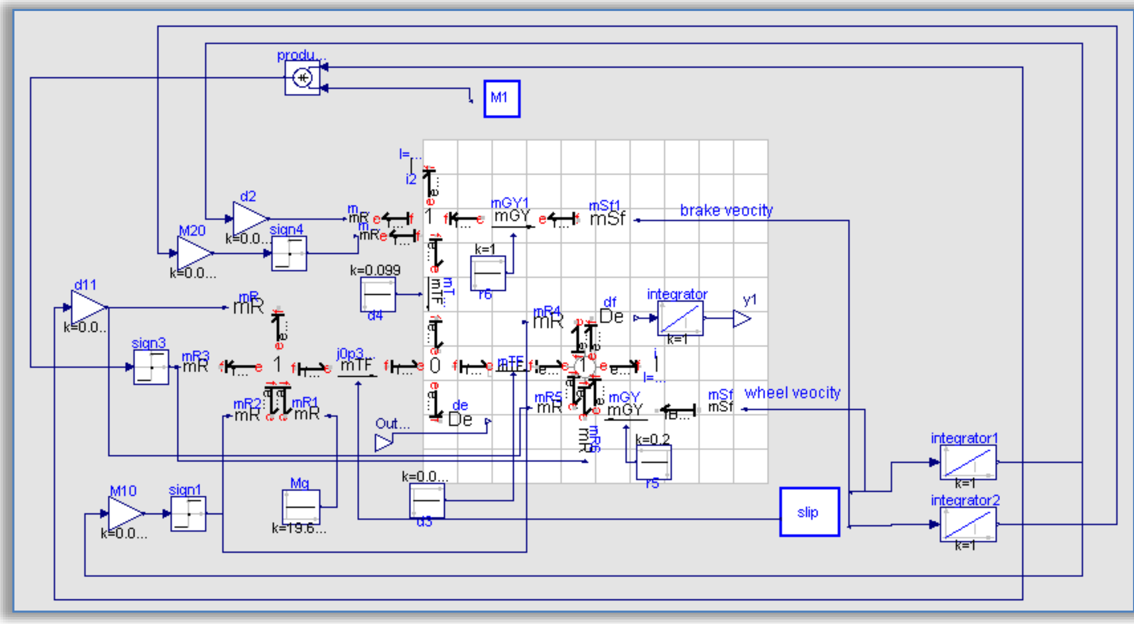

Figure17: Complitely bond graph model for model of ABS

3. FUZZY CONTROL ALGORITHM

The procedure of the fuzzy logic control is making the control designs are setting the constraints, assigning the linguistic variables to inputs and output, setting the rules for the controller. Slip variable and acceleration of the wheel as inputs whereas the output variables of this controller are the turn-on time period of the ABS. The objective of the designed controller is to control as per desired turn-on time period of the ABS, these had to be changed by fuzzification through membership function (μ).

Rule for ABS control:

1. If (input1 is N1) then (output1 is 1)
2. If (input1 is D) then (output1 is 2)
3. If (input1 is H) then (output1 is 3)
4. If (input1 is R) then (output1 is 4)
5. If (input1 is R) and (output2 is 1) then (output1 is 5)
6. If (input1 is R) and (output2 is 3) then (output1 is 6)
7. If (input1 is R) and (output2 is 4) then (output1 is 7)
8. If (input1 is R) and (output2 is 2) then (output1 is 8)

The Fuzzy control system has been formulated with two inputs and delivers single output as follows:

- Input 1 - Slip function on the second wheel in time depending (road imitation), Figure 19
- Input 2 - Acceleration of the wheel in function of the time,
- Output - ABS preasure in function of the time

Both the inputs have membership functions. Triangular functions are used as they are the most conventional and easy to implement. There are four membership functions for slip:

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1. N_1- Slip increase of acceleration
2. D - significantly increase
3. H - proportional increase
4. R - slight decrease

Secund membership function for accelertion are:

1. 1-No ABS
2. 2 -ABS hold
3. 3 -ABS realise
4. 4 -ABS fall

The fuzzy system will determine the output by evaluating the defined rules of the membership functions of the inputs.

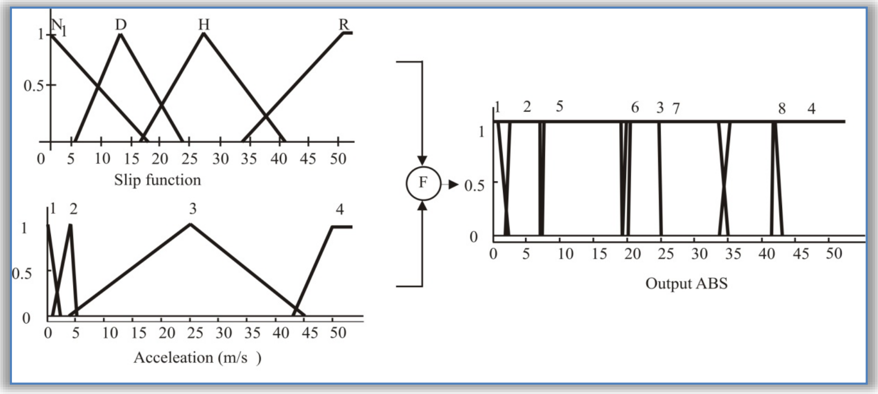

Figure 18: Membership and output functions for fuzzification

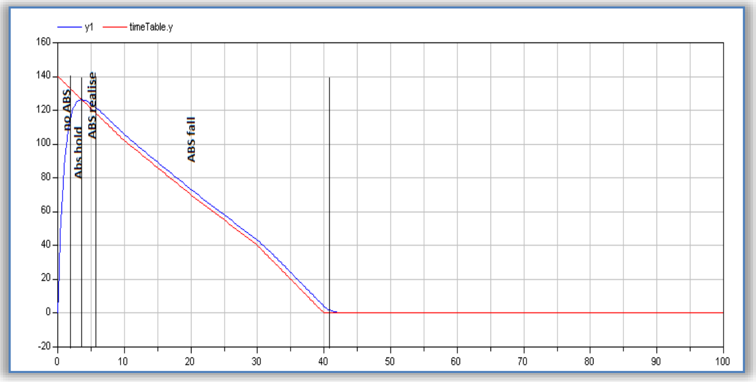

Figure 19: Membership functions for fuzzification of acceleration input

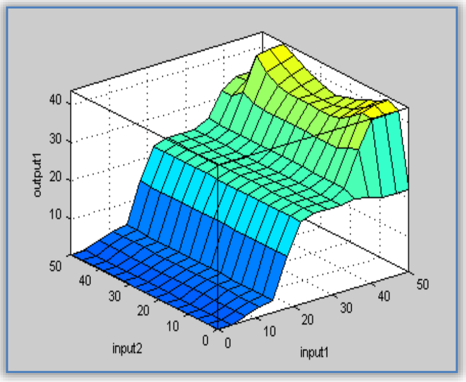

Figure 20: Surface view of the control area

4. EXPERIMENTAL RESULTS

In order to determine simulations making fuzzy control we made set of Dymola block in Simulink given in Figure 21. A Fuzzy controller for each wheel is used to keep the slip ratio within its stable region. The inputs to the controller are the wheel slip and the wheel angular acceleration. The Fuzzy rules regard the latter input as a virtual criterion for the direction of slip variations.

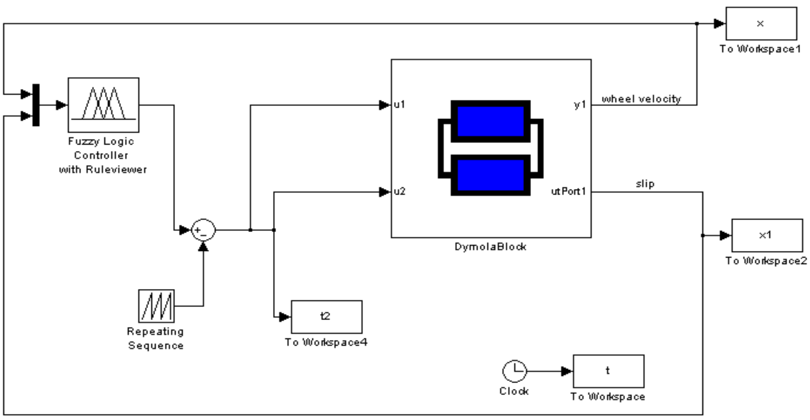

Figure 21: Block diagram of fuzzy control in Simulink

The output of the controller is the amount of torque weakening that should be devoted to the torque command of the motors, in order to prevent the tire to enter into its saturation region.

All experimental results with or without ABS are given in follow pictures:

Distance L as an angle φ and radiuses of the wheels are measured. Geometrical issue are given in following table.

Table 1: Parameter values used in simulation

R1 (m)	R2 (m)	ϕ (°)	L (m)	Mg (N)	J_1 (kgm^2)	J_2 (kgm^2)	d_1 (kgm^2/s)	d_2 (kgm^2/s)	M_{10} (Nm)	M_{20} (Nm)
0,0995	0,099	65,61	0,37	19,62	0,00753	0,0256	1,874 10^{-4}	2,1468 10^{-4}	0,032	0,0925

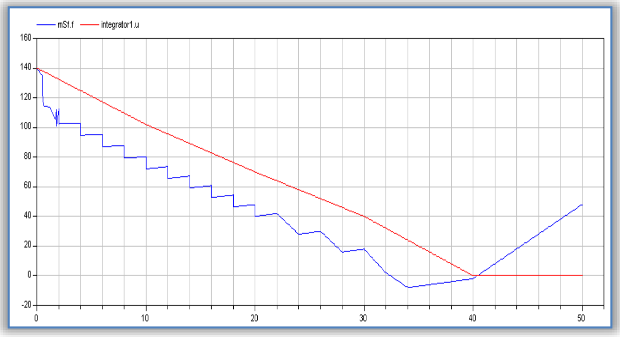

Figure 22: Velocity of the wheel –without (red line) and with (red line) ABS

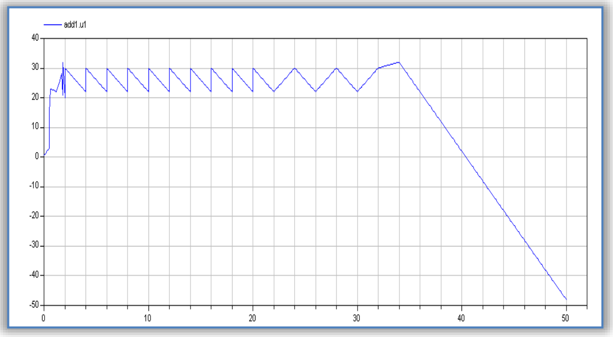

Figure 23: Simulation of output fuzzy control

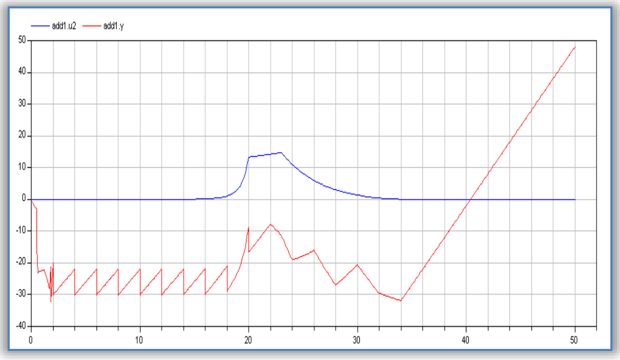

Figure 24: Slip function before (blue) and after fuzzy ABS control (red line)

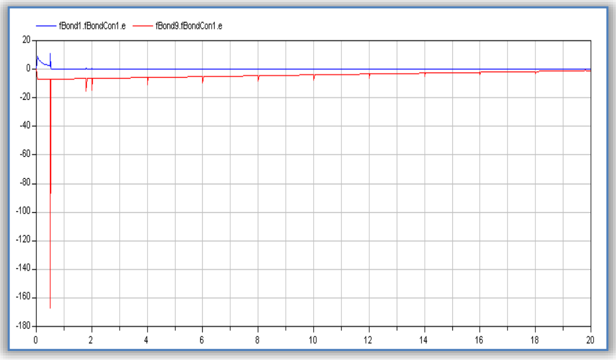

Figure 25: Longitudional force (blue line) and normal line (red line) after ABS control

5. CONCLUSIONS

In this paper are shown project of fuzzy control with slip regime against brake block of ABS. The mathematical description in nonlinear domain are modified in hybrid bond graph scheme, and new verification of the proposed approach in the management of digital simulation in Dymola was performed and real experiment. The introduction of the fuzzy control in ABS, knows it significantly improves the characteristics of the nonlinear system, as it is shown in simulation results. It is confirmed the good performance of the control algorithm in comparison with traditional solutions.

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