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Anti-Lock Braking System Components Modelling

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Abstract: ***Anti-lock braking systems are widely used in modern vehicles and provide safe driving for many different road conditions. Tire skidding occurs unexpectedly as a result of non-linearity in the system. The system behavior can be modelled and simulated using simulation software, which would help to visualize the system behavior. It would lead to obtaining optimum brake performance as well as safe driving. Modelling and simulation methods that can be used with every component of the system are presented. A variety of simulation software has been discussed.***

Keywords: ***Anti-lock brake system; ABS; brake control; modelling; simulation.***

I. INTRODUCTION

The Anti-lock braking system (ABS) is commonly used in modern vehicles. It provides safe driving which could prevent accidents from happening. Many ABS control schemes have been advanced since the 1950s [1]. Currently, the development of safety systems has become a main concern in the automotive industry as a result of the increase in vehicle accidents [2]. In addition, other systems such as four-wheel steering [3], traction control (TC) and many others that work hand in hand with the ABS are equipped on vehicles [4]. These systems do not only secure the driver, but they also protect pedestrians [5]. Nowadays, ABS and electronic stability control (ESC) are compulsory for both vehicles and trucks [6]. The function of the ABS is to prevent tires from locking by controlling the wheel slip ratio [3]. Front tire locking causes an oversteer phenomenon, whereas rear tire locking introduces understeer which might spin the car around [7]. An ABS enables the driver to steer the vehicle when the brake is abruptly applied, therefore keeping the vehicle safe and stable [7].

The ABS can be mathematically described as a model to be tested and developed. This system consists of a set of components that work together to reduce a vehicle's speed until it stops. The system contains mechanical and electronic parts. Figure 1 illustrates the ABS construction.

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The mechanical components are a pedal, master cylinder, disc, pads and tires. The electronic parts are sensors, actuators and a controller. Controlling the brake's hydraulic pressure keeps the slip ratio at an ideal level without tire skidding [8]. In the ABS control development, obtaining an ideal slip ratio is the target that is usually set to be achieved [9].

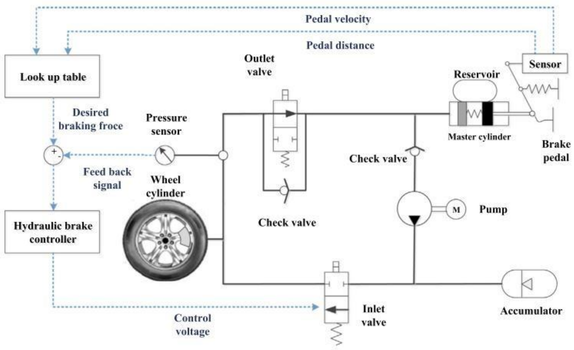

Fig. 1.ABS layout [10]

There are many control strategies applied to ABS controls. Fuzzy logic is one of these control methods [11] and is likely to be the most privileged control strategy for the ABS [1] as it is categorized as an intelligent method used for the system's control [12]. It is a smart methodology which works with non-linear complex systems that are quite difficult to be modelled mathematically [1]. Two elements would cause non-linearity of the ABS which are the coefficient of friction and road conditions [13]. Neural network has also been used for system control and attained meaningful outcomes [14]. The mix in using different control strategies, for instance, a sliding mode control (SMC), fuzzy control, optimal control, and adaptive non-linear control are found in ABS researches [13]. A PID controller can be used with this non-linear system to decrease the stopping distance and the longitudinal slip [15]. Fuzzy PID controllers are fitted in many cars to manage multiple systems [16].

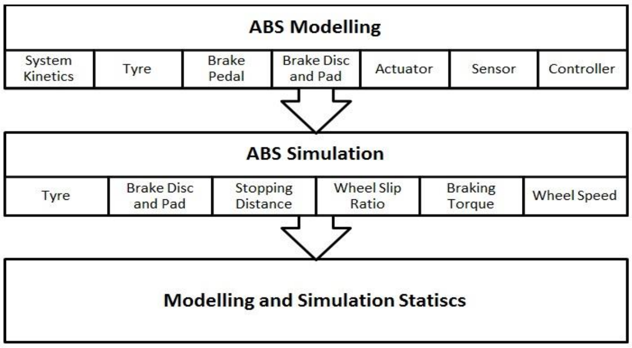

Fig. 2.Subtopics arrangement.

A fuzzy neural network uncertainty estimator has been used to estimate non-linearity of the ABS [17]. A system which is built on SMC needs to define the bounds of uncertainties [18]. Besides, the uncertainty would occur as a result of mass and road gradient variation [13]. This paper presents the methods used in ABS modelling. It covers modelling of the ABS components. It is structured as it is depicted in figure 2 and is created to become a baseline for ABS modelling and simulation research.

II. ABS MODELING

In order to start developing an ABS, modelling the system should be conducted first. This would save time, effort and money. While this system contains many components, simplifying its model by neglecting some parameters might be helpful in some cases. Determining inputs and outputs of the system is rather important to obtain meaningful outcomes.

A. System Kinetics

Considering the quarter vehicle model is sufficient for ABS modelling, using such a model is beneficial to correlate between the wheel acceleration, normal load, braking force and multiple damping ratios [8]. The braking force is distributed upon the four tires of the vehicle. Kinetics of the quarter vehicle model is shown in figure 3. Most of the brake models do not take the other resistance into account, such as aerodynamic force, which might decrease the braking performance [19]. In principle, the longitudinal force depends upon the wheel slip ratio, even if the ratio is small, but it changes correspondingly [9]. Furthermore, for easing system computation, some variables such as rolling and aerodynamic resistance and passive movement of the rotation axis are usually excluded in literature [20].

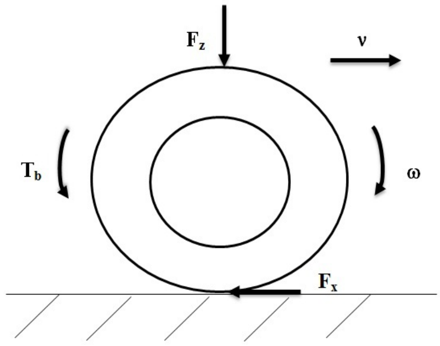

Fig. 3.Quarter Car model.

When modelling a complex system, variables do not remain constant, therefore, the equation needs to be modified accordingly [2]. The wheel angular speed and vehicle speed are assumed as degrees of freedom [8]. The longitudinal dynamics of the wheel is formulated in the following equation [8]:

$$m\ddot{\omega} = -\mu(\lambda)F_z(t) \tag{1}$$

The wheel angular rotation is derived from the following equation [21]:

$$I_w\ddot{\omega}(t) = \mu(\lambda)R\, F_z(t) - K_b\, P_b\,(t)R \tag{2}$$

The right-hand side of the equation (2) represents the friction and the braking torque [21]. The angular acceleration and braking pressure are derived from the previous equation and described in the following equation [8]:

$$\ddot{\omega}(t) = \frac{R}{I_w}\,\mu(\lambda)R\, F_z(t) - K_b\, P_b\,(t) \tag{3}$$

$$P_b\,(t) = \frac{\mu(\lambda)R\, F_z(t) - I_w\,\ddot{\omega}(t)}{K_b} \tag{4}$$

The difference between the wheel acceleration and brake pressure can be calculated by the next equations [8]:

$$\Delta\ddot{\omega}(t) = \frac{1}{I_w}\,\mu(\lambda)R\,\Delta F_z(t) - K_b\,\Delta P_b\,(t) \tag{5}$$

$$\Delta P_b\,(t) = \frac{1}{K_b}\,\mu(\lambda)R\,\Delta F_z(t) - I_w\Delta\ddot{\omega}(t) \tag{6}$$

The difference between the wheel friction coefficient can be obtained using this equation [21]:

$$\Delta\mu(\lambda) = \frac{1}{R}\frac{\Delta\ddot{\omega}(t)+\Delta P_b\,(t)K_b}{\Delta F_z} \tag{7}$$

B. Tier

There are many aspects that should be taken into consideration while tire modelling. Tire modelling is a difficult task due to its non-linearity and viscoelasticity [22]. The tire has lateral, vertical and longitudinal forces acting on it [22]. Tire dimensions should be identified during the modelling process [23]. Moreover, its structure could affect the ABS performance. Tire tread stiffness affects the slip ratio [24]. Hyperplastic is the material used for tire modelling [23]. Modelling the tire rim, reinforcement, internal air pressure, road surface contact, tractive force and setting the tire as a solid object are the aspects which can be utilized at modelling [23]. Lugre tire models are used to approximate the road friction condition [25]. While tire modelling, the road friction is recommended to be neglected to obtain significant results of other factors [26]. Rolling resistance is directly proportional to tire pressure [27]. The variation of the tire pressure which occurs while the tire is moving seems to have an influence on the friction coefficient [28]. In literature, the tire adhesion coefficient is always identified [29]. The relationship between the tire and road surface can be expressed using the Pacejka model. It is noted by tire magic formula and used for evaluating the moment and tire steady-state forces [30]. The experimental equation is expressed as follows:

$$Y_{Pcj}(x) = D\,\sin[C\,\arctan B_x - E(B_x - \arctan B_x)] \tag{8}$$

It is not easy to classify the magic formula parameters due to the fact that it contains trigonometric and inverse trigonometric functions [14]. Other models which are taken from the Pacejka model, such as starched string and contract mass, could be used with an ABS [22].

C. *Brake Pedal*

The brake pedal amplifies a driver's depressing force and transfers it to the brake master cylinder. Changing the pedal,

disc or hydraulic piston geometry will vary the braking force [31]. The brake pedal is linked to the master cylinder and is considered as a solid body. This is shown in the following equations [32], [10]:

$$F_p = k_p X_p \tag{9}$$

$$M_p \ddot{X}_p + C_p \dot{X}_p = F_{pi} - k_{ps} X_p \tag{10}$$

D. *Brake Disc and Pad*

Brake discs and brake pads can be modelled in many different ways. The structural model of the brake disc is utilized for brake disc heat transfer simulation. It is also helpful in identifying deformed parts [33]. Overheating of the brake disc and caliper causes non-linearity on the brake system [22].

E. *Actuator*

Brake actuator allows the hydraulic pressure to pass through the ABS circuit as per a command signal received from the brake controller. The brake pressure rate of change is proportional to the flow rate of the brake fluid; meanwhile, the flow rate is dependent on the opening of a control valve [1]. Initial condition values cannot be chosen randomly as a consequence of its sensitivity at optimization [14]. For some applications, the hydraulic pressure that goes to the wheel cylinder can be controlled up to 5 bars [34]. Approximating the initial values requires lots of engineering practice [14]. The electric actuator, which is used for regenerative braking, performs faster than the friction brake [7]. However, switching off the actuators at declaration will disable the regenerative brake, and as a result, the ABS will rely on the friction brake [7]. An electro-hydraulic actuator should have performance tracking as well as fast response time [32]. The potential difference between the electromagnetic control coil and the hydraulic pressure can be calculated by the following equation [10]:

$$u_{Act} = L\,\frac{di}{dt} + ri \tag{11}$$

The wheel slip of each wheel can be controlled individually while using brake actuators [35]. When braking, the gas inside the hydraulic accumulator experiences an adiabatic process and, therefore, the gas state equation can be applied and the polytrophic index can be selected 1.4 [36]:

$$P_0 V_0^n = P_1 V_1^n = P_2 V_2^n = const \tag{12}$$

F. *Sensor*

Wheel speed is measured by an inductive coil sensor that is fitted to a reflecto r ring [8]. Rate and accelerometer sensors have recently been used for wheel slip control [7]. Sensors have different working principles as they either work by sound, microwave or light in order to detect road conditions [37]. Sensor and actuator noises are neglected in ABS research, although adding a Kalman filter would reduce noise and wear [5]. To obtain an ideal performance of a wheel speed sensor, its transfer function should be linearized in the frequency domain [38].

G. *Controller*

Adaptive fuzzy logic is the method used for a non-linear continuous time, bu t it is not suitable for discrete time [39]. The ideal value that is regularly chosen for the friction coefficient μ is 0.2 [1]. It is suggested to use the tire-force curve when programming the brake controller [40]. Figure 4 shows the ABS control block diagram:

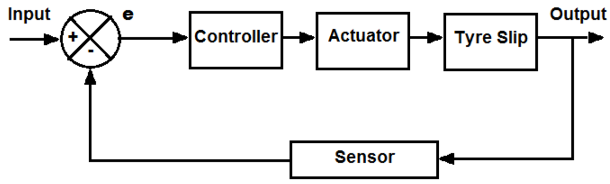

Fig. 4.ABS Control Block diagram

Logging the driving behavior and using it for the control system is useful for development [16]. The tire angular acceleration and velocity can be derived from the signal that comes from the wheel speed sensor [22]. Parameters of a membership function can be selected by using a Takagi-Sugeno-Kang model [1]. There are systems such as RT2500 inertial and Global Positioning System (GPS) navigation provided by OxTS that can be used to measure the vehicle tilt angle as well as longitudinal and lateral velocities [4]. When braking, the speed of the tire becomes less than the speed of the vehicle which is known as $\boldsymbol{\lambda}$ [9]. Maximum braking force relies on the tire friction coefficient [30]. Figure 5 shows the ABS constructed as blocks in Simulink.

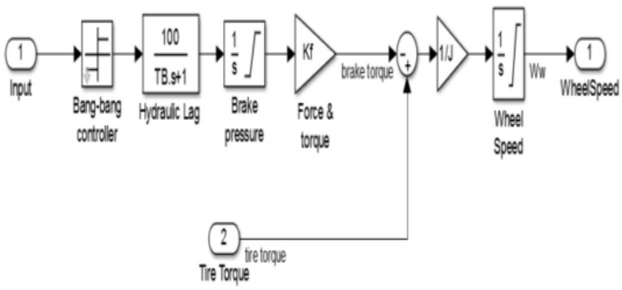

Fig. 5.Brake dynamic in Simulink for braking system with ABS [1]

In a vehicle, there are many control systems performing simultaneously. For this reason, modelling the vehicle lateral, vertical and longitudinal dynamics is highly important [41]. One of the significant characteristics while developing the system is to choose the degree of freedom to ensure its durability within its allocated memory [41]. P and D parameters could have more effect on the PID controller performance [42]. Multi-input and single-output controllers use the fuzzy logic controller where tire slip and vehicle velocity are inputs [43]. The road friction can be predicted by utilizing the signal fusion methods [44]. The ideal value that is regularly chosen for the friction coefficient μ is 0.2 [1]. Each optimization algorithm would have an influence on the tire model parameters and computing precision [45]. An ABS can be modelled by using the bond graph method [46]. Lumped disturbances can be approximated by using the inertial delay control method [47]. When the braking rotation speed is smaller than the wheel speed, longitudinal slip $\boldsymbol{\lambda}$ happens. This is illustrated in the following equation [48]:

$$\lambda = \frac{v - R\dot{\omega}}{v} \tag{13}$$

An ABS design for off-road is complex with a regenerative brake[6]. For estimating non-linear systems, a piecewise linear system could be used [32].

The ABS decreases the hydraulic pressure on tires while the electronic stability control produces the pressure again [5]. Maximum overshot, response error and rise time are crucial outcomes of any non-linear system [49]. The Lyapunov adaptive control method is not adequate to discrete time applications [39]. When using the barrier Lyapunov function control method, tire friction coefficient can be set as an input of ABS [31].

Longitudinal slip and angular velocity are the variables needed for a controller [22]. The methods which are currently used for an ABS are not flexible to the changes in the road conditions [17]. A normal load could consider variables to include the suspension system at simulation [25]. The conventional PID controller can be tuned by the use of a hit and trial technique [50]. When the car is driven on rough roads, sensors create fluctuated signals, and consequently, the ABS will stop functioning [6]. Turning of the ABS will decrease the responsive torque when driving off-road [6]. Categorizing and analyzing the closed-loop system of linear systems were the initial success of the adaptive control [39]. The adaptive control can estimate and compensate uncertain variables, unlike the robust control [39]. There are many strategies applied for controlling the ABS, for instance, the fuzzy control, the neural network and switching control, and the linear and non-linear control [51]. Non-linearity of the ABS is caused by tyre saturation, un-modelled dynamics, a variety of vehicle factors, and tyre friction coefficient [18]. The ABS might become an obstacle for off-road driving conditions [22]. SMC and logic threshold controls are used to prevent the wheel from locking [9]. For tackling uncertainties in closed loop systems, many control methods have been developed [39]. Digital computers accept control algorithm which is computed in digital form [39]. Combining a robust prediction controller with a radial basis function neural network (RBNN) would provide better control performance than the sliding controller [17]. The fuzzy genetic control system provides efficient control by allowing the pressure to reach the desired value [20]. The fractional order sliding mode controller (FOSMC) adaptive system shows uncertainties for adaptable and predictive slip ratio [52]. The tuning method of the fuzzy logic controller can be taken from the Lyapunov theory. Below 8 km/h, the ABS turns off because the sliding distance to the wheel lock is negligible [48]. General regression neural network (GRNN) and Bayes' theorem could be implemented to estimate the road/tire friction coefficient rather than using a complex tire model [53]. Neural network is exact and adapted for the magic formula of the tire model [14]. Radial basis function neural network can be used after approximating the uncertainties [18]. The sliding mode controller provides robust performance, although instability of the road coefficient [54]. The producing braking forces rely on tire surface contact [55]. The Takagi-Sugeno hierarchical fuzzy-neural mode can be used to decrease the processing time of the controller as well as the control rules [56]. The tire grip is achieved by using a Kalman-filter-based estimation algorithm [15]. The stopping distance should be within the International Organization for Standardization (ISO) 21994 regulations [57]. An on/off solenoid valve is used in lorry braking systems rather than a proportional solenoid [58]. The new Braking emergency system could increase the stopping distance in some cases when it conflicts with the ABS role [59]. To optimize the rules of the fuzzy controller, the Particle Swarm Optimization algorithm is applicable [60]. It is convenient to be used with complex systems derived from certain cost functions [61]. The control algorithm can be simulated in State flow block found in the Simulink library [62]. Linear Matrix Inequality and pole placement are two methods used to verify the fuzzy logic control system performance [63]. The PID controller is more attractable due to the ease of use and great real-time constraint [1]. The neural network has the potential to be used with non-linear controls because it has a good parallel distributed processing [39]. It will continue working while facing and solving system errors [39]. It is more practical for hardware implementation and has adaptive learning capabilities [39]. The Q-learning control can easily be utilized in an ABS because it does not require a primary controller for stabilizing [51]. Super-twisting sliding mode algorithms can be used for ABS control [64]. For other applications used in electric vehicles (EV), super capacitors are used for obtaining optimal braking performance [65]. Using a sensing technic for measuring the distortion of the axle bearing due to the loads would offer better tire slip control [66]. To control the pressure oscillation which occurs in the master cylinder, a variable sinusoidal signal is sent to the ABS motor [67]. The parameters used to formulate the control algorithm are the wheel slip ratio, longitudinal and vertical force [68]. The ABS inputs are wheel acceleration and wheel brake slip. The output control signal is sent to the actuator [20]. For superior ABS performance, the slip ratio should be kept close to the ideal value [69]. Tracking performance of the braking force using mean square error is expressed in the following equation [10]:

$$e_Y = \frac{1}{t}\int_0^1 (Y_d(t) - Y(t))^2 \tag{14}$$

The differential equation of PID controlled is [10]:

$$u(t) = K_P[e(t) + \frac{1}{T_I}\int_0^t e(t)dt + T_D\frac{de(t)}{dt}] \tag{15}$$

Next, the transfer function to be added to MATLAB/Simulink is as follows [17]:

$$K_{PID}(s) = P + I\frac{1}{s}D_v\frac{N}{1+N\frac{1}{2}} \tag{16}$$

The tracking error is calculated as follows [17]:

$$e(t) = \lambda(t) - \lambda_{opt}(t) \tag{17}$$

Modern controllers require signals calculated in digital or discrete time [39].

In the Proportional–Integral–Derivative controller (PID) P is related to the error that happens in the present, I show the error collected from the past, and D indicates the predicted upcoming error [1]. The integral control method rises the system order [17]. Signals come from sensors and should be filtered in order to become smooth [8]. A set-point filter can be used to minimize overshoot signal [70]. Longitudinal velocity is counted according to the ratio between the wheel angular velocity and wheel radius with almost neglected tire deformation [71]. Neural network controls perform better than other controllers when controlling uncertain non-linear systems [39].

The controller could be given more details such as the difference in vertical load and tire road conditions [21]. The neural network tire model can be used for low speed and a small steering angle, on the other hand, the magic formula is most convenient for high speed and big steering angles [14]. The fuzzy logic method describes the system linguistically. There are three steps that lead to building a fuzzy controller. These are fuzzification, defuzzification, and rule base [1]. However, outputs and inputs of the system should be identified at first. Next, each membership function has to describe the condition of the inputs to the output. For example, assuming that the input is the wheel speed sensor and the output is the signal that is sent to the hydraulic actuator, it could be said as a rule that when the speed sensor is positive big, the hydraulic pressure is also a positive big. Table I demonstrates the membership function names of a fuzzy logic controller.

Table- I: Membership classification [19]

Membership Function	
Short name	***Full name***
NB	Negative big
NMS	Negative medium small
NMH	Negative medium high
NS	Negative small
Z	Zero
PS	Positive small
PMH	Positive medium high
PMS	Positive medium small
PB	Positive big

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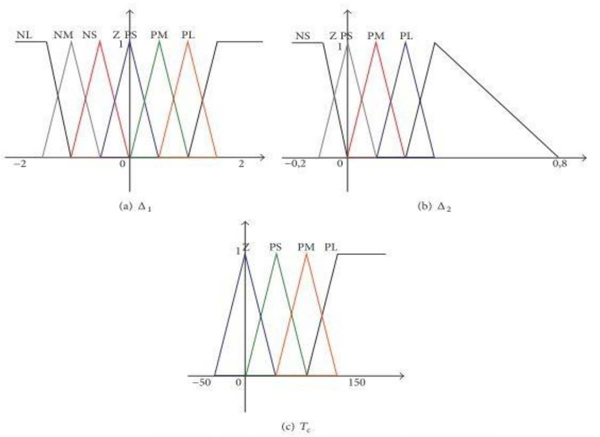

Fig. 6.Triangle membership functions of a fuzzy system[69].

Increasing the membership function would give a higher accuracy. However, not every input and output requires a lot of membership function. Moreover, the shape of the membership function should be taken into consideration. Choosing a triangle or trapezoidal shape would vary the system response. Figure 6 presents the membership function of the inputs and output of a fuzzy logic controller.

III. CONCLUSION

The ABS could be modelled and simulated by using computer software and can be formulated mathematically. The equations used for system components were gathered. Some control strategies applied to the system were discussed. Some parts of the system were simulated by many different simulation software. Simulation of stopping distance, wheel slip ratio, brake torque and wheel speed were presented. Some statistical analysis of the software used for the simulation were demonstrated. The modelling and simulation of the system would give better comprehension of how the system works and could be very helpful in system development. This will help to obtain an ideal braking performance and safer driving.

NOMENCLATURE:

m	Mass of a quarter vehicle model
v	Wheel longitudinal velocity
F_x	Longitudinal tyre force
T_b	Braking torque
μ	Friction coefficient
F_z	Normal force on the wheel
K_b	Brake gain
P_b	Brake pressure
R	Wheel radius
λ	Wheel longitudinal slip ratio
λ_{opt}	Wheel longitudinal optimal slip ratio
Y_{Pcj}	Force or moment resulting from a slip parameter
x	Longitudinal stiffness factor
C	Shape factor for longitudinal force
D	Peak value factor
E	Curvature factor
Y_{pcj}	Force or moment output
I_w	Inertia of the wheel
ω	Wheel angular displacement
$\dot{\omega}$	Wheel angular speed
$\ddot{\omega}$	Wheel angular acceleration
F_{pv}	Vacuum booster output force
k_p	Brake pedal stiffness
F_p	Pedal force
M_p	Pedal mass
C_p	Pedal damping coefficient
k_{ps}	Return spring stiffness of the pedal
F_{pi}	Vacuum booster input force
X_p	Input displacement of the pedal
u_{Act}	Amplifier output voltage
r	Actuator coil resistance
i	Electric current
L	Inductance of the coil
n	Polytropic exponent value
P_0	Pre-charging pressure
P_1	Minimum pressure
P_2	Maximum pressure
V_0	Volume of the gas at pressure P_0
V_1	Volume of the gas at pressure P_1
V_2	Volume of the gas at pressure P_2
e	Tracking error
Y_d	Lateral coordinate of a target brake
Y	Actual brake lateral coordinate
e_Y	Mean square error
N	Filter coefficient
u	Controller function
P	Proportional coefficient
I	Integral coefficient

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