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Review Article

Overview of Design of Wheel Slip Control Strategies of Antilock Braking System

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Abstract *- A review of the wheel slip control techniques for electric vehicles is the base of the present study. The main concern of electric vehicles is their reliability and safety. Antilock Braking Systems (ABS) is the safety element that keeps the wheels in tractive contact with the road during braking and avoids locking the wheels when the vehicle is braking or cornering. As a result, it prevents the car from skidding out of control and keeps it stable and steerable enough. Developing a control method to retain the slip of the wheel at the appropriate value is the primary objective of different methodologies. Correlation between the slip ratio and the adhesion coefficient exhibits nonlinear characteristics and unexpected behavior under different road conditions. Therefore, designing a robust control system for ABS is essential. An overview of the various control techniques used to enhance ABS performance is presented in this article.*

Keywords *- Braking force, Composite rule, Predictive control, Robust controller, Slip rate.*

1. Introduction

Antilock Braking System (ABS) is an important element of automobiles and is a crucial safety system during emergency braking [1]. A vehicle's wheels lock up quickly when it is braking. It increases the slip ratio (λ) of the wheel. The slip ratio is the function of the vehicle velocity (*Vv*) and the wheel velocity (*Vw*) and is specified as:

$$\lambda = \frac{V_V - V_W}{V_V}$$

The major cause of car accidents is the locking of the vehicle's wheels during braking. The locked wheels experience sustainably reduced force of friction. This is the cause of the vehicle's uncontrollable motion when it is sliding on the road. Locking wheels is troublesome as it increases the stopping distance, makes steering difficult, and causes the vehicle to lose control [2]. The Antilock Braking System (ABS) avoids the locking of wheels during braking, maximizing wheel traction and maintaining adequate vehicle stability and Steering ability [3]. ABS ensures that the brake pressure applied at the wheels during braking is just below the point at which a wheel locks. Thus, it ensures that the vehicle is stopped with the minimum stopping distance. The frictional forces produced during the braking or acceleration are proportional to the vehicle's normal load. This proportion is known as the adhesion coefficient (μr). For different road conditions, the slip ratio varies widely. The characteristics between slip ratio (λ) and coefficient of adhesion (μr) exhibit strong nonlinearity and uncertainty [4]. Hence, the ABS problem cannot be solved using traditional frequency domain linear methods. It requires a controller to enhance the tractive force of the wheels, optimize the slip ratio, and get the best possible lateral force from the road's surface. The controller must also reduce the braking time and distance and increase the vehicle's stability.

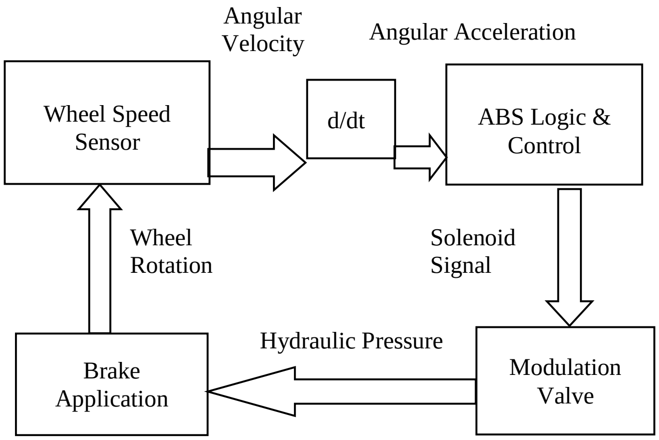

Fig. 1 Block diagram of ABS

2. Control Methods of Antilock Braking System

Various control techniques used in antilock braking systems are classified into two categories: (1) control achieved by continuously modulating brake pressure and torque and (2) control achieved by modulating brake pressure discretely for each wheel [5, 6].

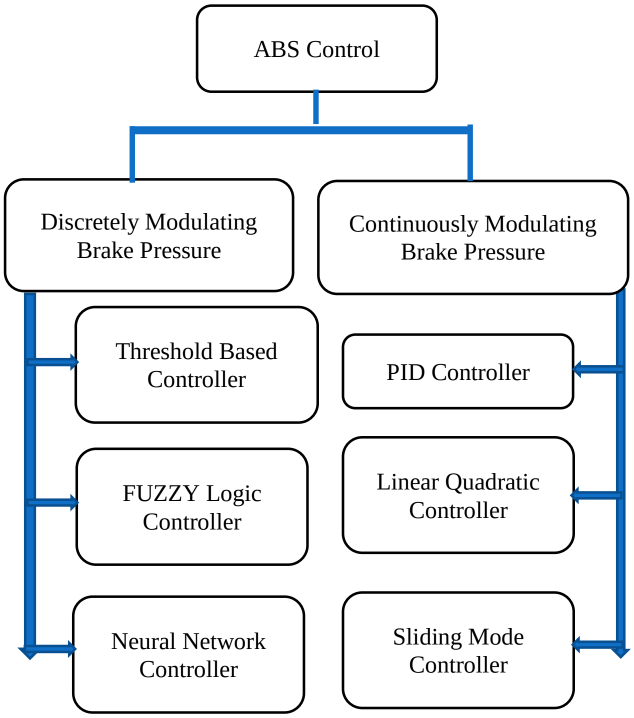

Fig. 2 ABS control methods

2.1. Dynamic Threshold Based Controller

In threshold-based controllers, the states are linked to certain control actions that were previously described. The state transition is initiated when the control variable goes beyond the predetermined threshold. The brake pressure control actions are defined as "(i) apply, (ii) release, and (iii) hold" [7]. The output of the friction estimator is used to modify the logic. The threshold needs to be re-evaluated for friction levels of different road conditions. The threshold-based controller becomes more complex due to the insertion of functions affecting the jerk compensation, and delays are produced in the yaw moment when driving on μ-split roads, braking operation during turning and rough road braking. The controller neglects the side effects proposed in [8]. The algorithm proposed is robust to the measured noise. The pressure derivative is used to predict the delays in the operation. However, it includes more tuning parameters. It cannot prevent acceleration from exceeding a predefined threshold due to time delays.

2.2. Fuzzy Logic Controller

Strong nonlinearity in the tire behaviour and uncertain, noisy state variables are associated with the antilock braking system. Fuzzy logic is used in ABS control to overcome these issues. Fuzzy Logic Controller (FLC) deals with uncertain situations. The three steps of the FLC system are fuzzification, inference, and defuzzification [9]. The fuzzy controller generates the error signals (crisp inputs) during the fuzzification process and compares them with the predefined fuzzy set [10]. The input-output map is designed using a predetermined set of logic rules. Ultimately, the output undergoes defuzzification and is converted to a precise real value. Combining fuzzy logic with traditional control methods is a simple process. The large memory storage requirement of the controller is the only drawback.

2.3. Neural Network Controller

Neural Networks (NN) controller is proposed to address ABS variability and nonlinearities [11]. NN controllers use test data to train the NN. The neural network's hidden layer is adjusted to match every related input and output pair in the training set. Additional layers can be added to the network according to the application's needs. It increases its complexity. Neural networks have the advantage of tuning from training data. However, this characteristic may also lead to a fundamental flaw. For the neural network-based techniques to reliably assess the impact of control operations, the system needs to be properly instrumented during network training. Acquiring the essential data in the ABS application to fully utilize neural techniques' potential is very expensive.

2.4. Proportional Integral Derivative (PID) Controller

The PID controller is the most commonly used in ABS. To make sure that the intended operating point is reached while maintaining the desired system performance, the P (proportional), I (integral), and D (derivative) gains can all be adjusted. However, if the gains are not adjusted properly, PID controllers do not provide the best possible control action and operate inadequately. PID controllers' drawbacks include their poor ability to handle nonlinearities, inability to respond quickly to significant disturbances, and lack of reaction to changes in process behaviour [12]. When employing the derivative term, the low-pass filters can reduce noise amplification. However, the filtering action is constrained by the derivative action's counter-action behaviour. Because of the aforementioned problems, PID controllers in the ABS regulation problem cannot operate efficiently under varying operating situations [13]. Replacing the PID controller with a tuned PID controller improves braking efficiency by reducing the braking time and distance [14, 15].

2.5. Linear Quadratic controller

The linear quadratic controller is a feedback controller. It addresses the issues of determining a state feedback control law that meets an optimality requirement for a Linear Time Invariant (LTI) system. Johansen et al. designed ABS control using a linear quadratic controller [16]. Gain scheduling and local linearization are essential for the control design. The control law uses integral action to remove a steady-state uncertainty and does not include a friction model. The vehicle implementation, however, revealed important restrictions on the highest gain tolerated before instability and the possible performance.

2.6. SMC- Sliding Mode Controller

The variable structure control system is called SMC. The sliding surface is the surface the system must force itself to reach and then stay on when it crosses a given state in the state space. An ideal sliding motion occurs when the system dynamic is restricted to the sliding surface. It leads to reduced-order dynamics other benefits like insensitivity to matched uncertainties and disturbances, and insensitivity to parameter changes. However, chattering or oscillations at high frequencies may occur from the sliding mode control action. It produces high actuator wear, instability, and energy loss [17].

Despite its drawbacks, SMC is regarded as a strong and effective controller for ABS applications [18]. A variety of strategies are implemented to reduce chattering in the ABS design. While these strategies successfully do so, they impact the controller's tracking performance and do not guarantee asymptotic stability. Lots of research has been conducted in the past to improve the performance of SMCs.

3. Control Strategies of Sliding Mode Controller

A Sliding Mode controller is associated with various problems. Novel control techniques are used in the research to overcome these problems associated with SMC in antilock braking systems. The following papers are chosen for the investigation of control techniques of SMC:

Deliang Yu et al. developed a dynamic model of single wheels for electric vehicles [19]. The four-wheel distributed drive system is developed with a compound brake anti-lock control system, including hydraulic and regenerative braking. It provides solutions to the problem of identification of pavement characteristics of complex road conditions during the deceleration of vehicles [20, 21].

The research is conducted to realize the effective use of composite braking systems to control continuously varying optimal slip rates. The estimation system calculates the optimal slip by monitoring the force of braking. The factors affecting the vehicle braking force are used to analyse the road conditions. The empirical recognition formula [22] is used for this purpose. The optimal slip rate evaluation method determines the slip rate [23].

The linear state observer estimates the optimal slip rate by recognizing the brake force applied and keeping it near the target value. The improved adaptive SMC regulates the torque, optimizes accuracy and reduces chattering problems. The sliding mode observer improves the stability and robustness of the system by modulating the slip rate. The regenerative braking system is used to provide quick and precise control. Simulation and laboratory tests are conducted by considering roads with different adhesion coefficients and roads with joint pavement and bisection pavements [2, 24]. The proposed controller can recognize the road conditions accurately and evaluate the best slip rate when conditions change.

Hongwei Wang et al. designed the improved global sliding mode controller to improve braking performance and control effect [25]. The controller's robustness is achieved when the system reaches a sliding surface. The use of SMC does not guarantee robustness. Also, SMC is associated with the chattering effect, which delays control signals [26, 27]. The global sliding mode surface overcomes these effects and improves stability. The control law proposed forces the trajectories on the sliding surface and holds them there for a predefined period.

Khatory Salma et al. described a global sliding mode control approach that regulates the wheel slip ratio [28]. Research is conducted to identify optimal gain values that can accurately track the desired wheel slip. Two distinct algorithms, Error Correction Learning (ECL) and Particle Swarm Optimization (PSO), are proposed to determine the controller gain.

A simulation uses traditional SMC and improved global SMC for dry and wet asphalt roads. The outcomes ensure better system performance during braking. Chattering is reduced by maintaining the optimal rate of slip. The suggested control strategy can successfully regulate the ABS and achieve global robustness. It improves braking performance. In conditions of wet asphalt roads, the suggested control strategy performs better.

Zejia He et al. recommended a Model Predictive Control (MPC) method [29]. A virtual dynamics wheel model is developed with an electric and hydraulic braking pedal. Hydraulic braking pedal provides safety in an emergency. Response is delayed when the braking mode is switched on. MPC-based antilock brake control strategy is proposed. It uses an electric motor as an actuator. It adjusts the slip ratio when it increases above the optimal value. The ideal slip ratio for various road conditions is calculated using a slip recognizer and sliding mode observer for linear braking [30].

The brake torque regulator traces the ideal slip for obtaining superior braking stability. The control unit and control law are tested on dry and wet road conditions. The suggested method works well for estimating and controlling the slip ratio during antilock braking and is appropriate for low-adhesion road situations.

Table 1. Comparison of control methods of ABS

Threshold Based Controller	Fuzzy Logic Controller	Neural Network Controller	PID Controller	Linear Quadratic Controller	Sliding Mode Controller
Time consuming	Time consuming	Extremely time and resource consuming	PID becomes unstable due to nonlinearities in the system	Sensitive to modelling errors	Better performance and robustness
Requires a large list of tuning parameters	Requires significant tuning of parameters and rules	Large set of training, data is required	Response delay due to large disturbances	Do not accommodate any feed forward action and beneficial for ABS application	Feed forward action restricts the operation of the controller

Yang Yang et al. established a composite rule made up of the dynamic and steady-state braking torque of ABS is established [31]. A Dynamic Coordinated Control technique is suggested for the ABS and regenerative braking. The coordinated control mechanism determines the braking mode. It ranges from emergency to small-intensity braking. The front and rear wheel motors offer the torque required for small braking signals. When applying the emergency brake, the brake controller detects the wheel deceleration (α) and slip rate (s) signals and shifts braking from regenerative to antilock mode. The ABS control module distributes the torque required for braking following braking coordination by computing s and α in real-time. Emergency braking is simulated considering both the suggested and conventional control approaches. The roads with varying adhesion coefficients are considered for simulation. Better braking performance and reduced stopping distance and time are obtained using the suggested control method. The suggested control approach recovers more brake energy than the usual control strategy.

Francesco Pretagostini et al. proposed a Predictive Nonlinear Model Control (PNMC) based on load sensing technology that works for three possible conditions of ABS: OFF state, ON state and ON state with Low Speed [4]. During the ABS inactive mode, the proposed controller acts as a follower of brake requests from the driver. For vehicle speed from 1 m/sec to V_{max}, ABS operates as a follower of the targeted slip. At speed below 1m/sec, the vehicle's dynamic becomes unstable and difficult to control. Hence, constant brake force is maintained to circumvent under-braking operations. Under normal working conditions, the controller tracks the reference slip. The under-braking operation is prevented at low-speed ABS mode by keeping constant brake torque. The proposed system is assessed on a comprehensive set of maneuvers. The comprehensive set of maneuvers is selected to consider all possible road conditions. The analysis of the proposed approach shows a considerable reduction in the braking distance with improved steer ability. The predictive nature of the controller enhanced steady-state stability and occupants' comfort.

Bo Leng et al. developed a control system for distributed drive vehicles [32]. The optimal rate of slip is maintained by continuously adjusting the anti-slip rate. The joint control variable uses quick, accurate, independent motor torque control to track its reference value. The application of the Lyapunov stability law to the estimation error's convergence is examined. The models are designed for kinematic estimation and dynamic estimation.

The dynamic model is used for a low rate of slip. The tire model is described as linear for low slip rates with negligible stiffness fitting error in the longitudinal slip. The dynamic model circumvents issues such as cumulating errors and the dependency on the data received from sensors [33]. The kinematic approach evaluates the vehicle's speed during a high slip rate. It is utilized in conjunction with a switching strategy and a slip rate controller to prevent mistakes in the sensor signals. The control law and the PI controller are the foundation for constructing the slip rate tracking controller. It manages input chattering and saturation, the nonlinearity of the model, disturbances and errors in the approximation and modelling.

The coefficient of angular acceleration and slip rate are joint control variables. Errors in the model lead to inevitable mistakes when assessing the slip rate. Wheel angular acceleration is added to address the loss of control effect. Lyapunov's theory establishes the tracking error's asymptotic stability. The simulation and testing confirmed the ability of estimation algorithms to estimate speed on high- and low-adhesion roads [34]. The chosen slip rate control algorithm ensures wheel stability, controls the quick increase in slip rate, prevents over-sliding, and enhances vehicle performance.

Pratik Chaudhary et al. proposed a Disturbance Observer (DO) with a sliding mode controller [35]. Maintaining appropriate slips for various road surfaces is the objective. SMC provides strong control over the nonlinear system. The uncertainty of slip dynamics and disturbances is estimated using the DO controller. The simulation is conducted for different road conditions and transitions. The suggested controller increases the adhesion coefficient and slip ratio, which improves vehicle performance during braking. The DO controller accurately tracks the preferred slip ratio with short time intervals for different road conditions.

Zhenpo Wang et al recommended a coordinated control scheme and Direct Yaw moment Control (DYC) [36]. Its stability is obtained by decreasing the braking distance during emergencies and difficult driving situations. The considered cases are the failure of braking actuators on low-adhesion roads and split roads [37, 38]. It consists of three controllers. The first develops maximum braking force. The direct yaw moment control produces the required yaw moment for the vehicle, the control strategies of ABS, and the constraint model. The second controller selects the side at which the maximum road adhesion control is required. Using the braking force allocation, the third controller generates the necessary yaw moment at the lowest workload on all wheels. Simulation and experimental results show better performance when the braking system fault occurs on roads with different surface adhesion coefficients.

Adarsh Patil et al. designed two methods based on estimating uncertainty for antilock braking systems [39]. The Inertial Delay Control (IDC) accesses the uncertainties and disturbances. IDC is used with the back-stepping approach for estimating derivatives and uncertainty of virtual inputs. In some techniques, an Inertial Delay Observer (IDO) based braking system is used to estimate the states in addition to uncertainty. Actuation lag's practicality is taken into consideration. Experimentation and simulation are used to test the schemes. The suggested techniques overcome some problems with the traditional back stepping and SMC for antilock braking.

Erkin Dincmen et al. used Extremum-seeking algorithm in the ABS control [40]. The road friction conditions are estimated using the extremum search algorithm. It is a self-optimization process which finds the maximum slip on the μ-λ curve. During longitudinal braking, the algorithm uses steering input to identify the operational zone of a tire based on adhesion coefficient slip ratio characteristics. It operates the tire close to the maximum value of slip. The operational zones of tires automatically adjust the lateral force and improves the vehicle stability when the driver requires longitudinal motion along with braking. The simulation demonstrates that the turning performance of the vehicle can be increased. The longitudinal tire force can also be significantly increased while applying a strong braking force.

Dzmitry Savitski et al. proposed four control techniques [41]. During barking, the Variable Structure Proportional Integral (VSPI) controller compensates for disturbances dependent on vehicle velocity and maintains specified level of the wheel slip. The First-Order Sliding Mode controller (FOSM) gets easily adjusted with In-Wheel Motor (IWM) control but causes oscillations and makes driving uncomfortable. When compared to VSPI and FOSM, the Integral Sliding Mode (ISM) controller has reduced oscillations, compensates for unmatched uncertainties, and improves braking performance [42-44]. The Continuous Twisting Algorithm (CTA) offers smooth control signals, but its application to brake systems with reduced bandwidth results in poor braking efficiency.

Yesim Oniz et al. proposed a Grey Sliding Mode Control (GSMC) technique to monitor the slip of the reference wheel [45]. Grey predictor determines the future output of the system. SMC makes required modifications to control the slip. The targeted wheel slip is considered constant. It is equal to the peak value of the adhesion coefficient. It is regarded as velocity dependent variable in this work. The ideal wheel slip value changes with the vehicle's velocity. The results of the experiments and simulations are confirmed. The suggested controller can manage uncertainties in the system, including measurement noise and disruptions. Thus provide stable braking operation and improved performance.

Babajide A Ojo suggested the speed estimation method using a Bang Bang controller for ABS is designed in [46]. The proposed system is simulated using a Bang-Bang controller to obtain the preferred slip ratio. The results with and without the controller are observed and compared. The ABS makes better vehicle stability and control possible with the Bang-Bang controller during lock-up. It also reduces stopping distance.

Lei Wu et al. suggested a method to control vehicle operation on ramp roads [47]. The method is suitable for quick and stable starting of vehicles on the slope. The dynamic allocation approach is implemented by examining the variations in the forces acting on the vehicle when starting on the ramp. Control reference for hill-start is established by knowing the forces applied to the vehicle when operating on the ramp. Real-time adjustments are made between the ideal and actual pressures using the logic control approach. A driving torque correction controller is designed to keep driving wheels from slipping. Simulation results confirm the suggested controller's outcomes and indicate a decrease in the vehicle's overall driving force and a rollback.

ABS with wheel speed sensors to differentiate angular velocities to retrieve the slip requirements of the control unit is designed in [48]. It is used to analyse the reference slip proportions using the evaluated vehicle speed and estimated wheel exact speeds. The friction coefficient is the primary factor determining how fast a vehicle should travel. Information on braking force is continuously obtained by sensors mounted on the wheels. Sensors determine the road surface conditions. ABS maintains the desired slip and ensures the vehicle’s steering ability when the brakes are abruptly applied.

The nonlinear characteristics of the brake system and other parameters affect ABS control. The value of wheel slip required varies all the time. The primary objective is to regulate each tire's wheel slip to maintain its targeted slip value. The complicated behaviour of the tire causes the wheel slip dynamic control to be nonlinear. In addition, the system experiences external environmental disruptions and suffers from parametric uncertainty. It makes the controller design for ABS very challenging. This results in the need for a controller that can handle these nonlinearities and uncertainties. The SMC can effectively handle the modelling uncertainties of the ABS [18, 49].

The SMC system converges quickly, is resilient against external disturbances and structural uncertainties, and is insensitive to parameter changes. However, chatter is a phenomenon brought on by sine functions in the control law, which can stimulate high frequencies and harm the system. A Fuzzy Sliding Mode Control (FSMC) is employed to overcome this problem. Through simulation, the effectiveness of FSMC is evaluated under various road surface conditions. Fuzzy logic can be used to enhance SMC's intelligence [50].

Elevated control signal oscillations are seen when the car is stopped, leading to the brake system's components deteriorating. Fuzzy Logic is a comprehension-based system that works well for incomplete models or systems with ambiguous data. The error ε is the fuzzy control output established using the sliding surface. The input and output for de-fuzzification are triangular and Gaussian membership functions. With increased tracking precision, the FSMC control method eliminates chattering and enhances wheel slip control performance for various road conditions.

The improved performance and quick response at a steady state are obtained by a controller that combines the reachability-based controller with the extremum-seeking algorithm based on bisection [51]. Errors in the estimate of the ratio of slip and coefficient of friction are eliminated by this algorithm. During braking operation, the ratio of slip and coefficient of friction is constant and appropriate information is gathered from transducers. The controller should ensure enough settling time as it influences the time required to identify the peak point by the algorithm. Simulation validates the robustness of this method, and the result shows a fast and effective implementation of the proposed system. It provides optimal braking performance, particularly with the measured noise and inaccuracy.

Kyoungseok Han et al. presented a wheel slip-based algorithm for ABS management [52]. The suggested method uses the characteristics of tire force and slip. Information about the slip and frictional force of the road is not required for the proposed method. Using quick dynamics of the wheel motors, an ideal front wheel slip is determined. The back wheels can follow the intended speed by observing the cycling pattern of the front wheel. The proposed system is validated through modelling and experimentation, proving its feasibility. It applies to any powertrain configuration.

Dzmitry Savitski et al. proposed the regenerative ABS architecture [53]. Different ABS configurations comprise standard hydraulic, decoupled electro-hydraulic, and mixed friction and electric braking systems as hardware. Experiments are conducted to validate the system, and improved performance is obtained.

Houzhong Zhang et al. used a Direct Yaw moment Controller (DYC) when driving on roads with extreme conditions [54]. The fuzzy logic algorithm is combined with SMC. The chattering effect is reduced when this controller is combined with DYC. Fuzzy control regulates the controller's parameters and enhances its capacity to adjust to various road conditions. In this study, the vehicle with distributed drive is considered. As the force of driving is controlled separately, DYC is easily implemented and gives precise control with a fast response [55].

The slide slip angle is estimated using a seven-degree freedom model of the vehicle. This model has different equations for yaw movement, linear and sideways movements, and the four wheels. The adaptive FSMC decides the yaw moment required during braking operation. This moment is assigned to each motor by identifying the load ratio of the wheel. Simulation is conducted to obtain experimental data. The efficiency of the control method is confirmed by relating its control technique and the results with SMC. The FSMC method provides better performance than traditional SMC. The switching gain in FSMC adjusts the parameters in real time depending on the system's sliding surface, state and relative position [56, 57]. Thus, it provides ideal control for any road condition and ensures stability.

A rule-based wheel slip regulation algorithm is proposed in [58] and experimentally evaluated in emergency braking and cornering maneuvers. The yaw rate control rule base is determined by varying the reference wheel slip value. The algorithm reduced the absolute normalized error in the yaw tracking rate.

The relationship between μ-λ is highly nonlinear, making ABS controllers extremely complicated. Obtaining prior information about the conditions of the road is difficult for ABS controllers. Two-time scale control system is used to overcome this problem [59]. The objective is to control the slip ratio to its reference and avoid locking the wheel. Different road conditions are determined using a fast time scale estimator. The ABS controller is designed using a fast time scale filter. Operation of the proposed controller is verified on high and low adhesion road, μ-split conditions. It is suitable for all types of roads and conditions.

4. Summary of Literature Review

Conclusions derived based on the literature review are as follows:

1) The design of ABS is complicated due to the noise in the data, uncertainties, variations in the parameters, etc.
2) In most works, parameter variations and uncertainties are not considered when designing the controller for ABS.
3) The adhesion coefficient varies nonlinearly compared to the slip ratio for various road conditions. The allowable braking force varies widely for various road conditions. Due to the bouncing of wheels on uneven roads, the slip ratio varies quickly. Due to all these effects, the design of the controller is complicated.
4) Significant delays are introduced by braking servo systems and actuators that limit the controller's bandwidth.
5) CAN bus communication causes a delay in the control action.
6) Threshold-based ABS controllers are time-consuming. The algorithm requires large tuning parameters.
7) A fuzzy logic controller is complex and requires many membership functions, tuning parameters, and rules.
8) To achieve the necessary performance, neural network-based controllers require large training data.

5. Proposed Methodology

The key stages involved in the design of the controller of ABS are:

- Establish a new dynamics model of the wheel considering all relevant factors affecting vehicle braking.
- Suggest a ground slip map to define the relation between the slip ratio and ground adhesion coefficient for different road conditions.
- Design a controller to regulate the slip ratio of the wheel for the Antilock Braking System.
- Validation of the proposed controller to verify its performance, followed by comparing the measurements obtained with known performance measurements of existing controllers of the Antilock Braking System.

6. Future Directions in ABS Research

The future of Anti-lock Braking Systems (ABS) is shifting towards more proactive and intelligent technologies. These technologies prevent the wheel from locking and optimize braking performance in a wide range of driving circumstances. Key aspects of the future ABS are:

- Implementing more sophisticated sensor technology for accurate and real-time detection of wheel slip can enable precise brake pressure adjustment on challenging road surfaces.
- The braking performance on uneven, wet, and icy roads can be optimized using braking strategies based on real-time road surface analysis.
- Integration with systems like electronic stability control and adaptive cruise control can increase vehicle safety.

7. Conclusion

The Antilock Braking System (ABS) is a crucial safety feature during emergency braking in Electric vehicles. It enhances braking efficiency by preventing the locking of wheels during braking. To obtain the best possible force from the road's surface, the ABS controller enhances the tractive force of the wheel and maintains the optimal slip ratio. This shortens the distance of braking and improves the stability of the vehicle. However, the nature of the slip ratio and the adhesion coefficient is nonlinear and unclear for different road conditions.

Control strategies are suggested to maintain the appropriate slip for various road surfaces and transitions. However, most of these methods need system models; some have chattering issues; and some cannot operate well enough for different road surfaces. Therefore, designing a robust control system is essential to reduce all the issues of ABS and to improve its performance.

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