

Performance Analysis of the ABS Control on Parallel Hybrid Electric Vehicle Equipped with Regenerative Braking System

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ABSTRACT

Anti-lock brake system (ABS) prevents the vehicle wheels from locking up and reduces the total stopping distance as far as possible. The current implementation is based on a traditional hydraulic disk brake and small wheel inertia. Seen the need for making vehicles cleaner in the future, it can be expected that an increasing the amount of vehicles will be equipped with electric motors able to regenerate energy during braking. The addition of this electric motor changes the properties of the brake actuation and has an influence on the wheel inertia. However, the objective of this paper is to study the change of the dynamics induced by the regenerative braking which assess the performance of traditional ABS systems on the parallel hybrid electric vehicles. The MATLAB software to establish the simulation model, which include the single wheel dynamic model, hydraulic brake system model, electric motor brake system model and traditional ABS controller were used. Moreover, an integrated control scheme for regenerative braking based on anti-lock regenerative brake system (ARBS) is implemented. Using ARBS, the braking and regenerative performances of parallel hybrid electric vehicle (PHEV) have significantly improved in slippery roads while the slip ratios are kept between 0.15 and 0.25. The simulation results show that the control scheme not only realizes the harmony and compatibility between electric motor brake and conventional friction brake, recovering the energy, but also fully takes the advantage of quick response of motor braking, better realizing the anti-lock braking control of vehicles. In addition, the simulation results also show that the hybrid electric vehicle (HEV) with the braking-driving integrated system has better ABS performances than the HEV with the traditional brake system, and has more the regenerative brake system (RBS) efficiency than other regenerative braking systems.

KEYWORDS: PHEV, anti-lock braking system, RBS, wheel slip control, PID control, wheel slip dynamic model, continuously variable transmission (CVT), anti-lock regenerative brake system (ARBS)

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1. INTRODUCTION

The use of electromechanical brakes (EMB) in combination with regenerative braking for parallel hybrid electric vehicle (PHEV), where braking force can be distributed to front and rear axles according to an optimal curve instead of a linear line was proposed. Therefore, more braking force will be distributed to front axle, which will offer more kinetic energy for regenerative braking. Fuzzy logic control was used to allocate braking force between regenerative braking and electromechanical braking. Moreover, antilock braking control of EMB was studied to maintain safety and stability of a vehicle using sliding-mode control with switching gains fuzzy adjusting [1].

Hybrid electric vehicles (HEV) were considered as the most cost effective solution, in the short term perspective, for the achievement of improved fuel economy and reduced emissions. The generative braking in a mild hybrid powertrain with infinitely variable transmission (IVT) and specifically on how its control strategy can be formulated and optimized was studied. This study was conducted

using a previously validated fully dynamic powertrain model. An initial investigation of the vehicle dynamic behaviour under braking conditions was served as the basis for the development of a control strategy for best braking performance and maximum energy recovery. The implementation of which, required a fully active and integrated brake control system. Limitations and constraints due to driveline configuration and driveability issues were considered and their effect evaluated. Simulation results were shown that fuel consumption reduction of 12% was achievable along a standard drive cycle [2]

The possibility of recovering vehicle kinetic energy is one inherent advantage of HEV, where the introduction of electric regenerative braking, the structure, design and control of a hybrid electric vehicle is quite different from the pure mechanical braking conventional vehicles. The key component of the regenerative braking system was investigated and a coordinated control strategy was proposed. The results provide strong supports to the design of the braking force distribution strategy for the HEV. This strategy can recover more

braking energy. The proposed strategy was verified through the simulation and the simulation results show that the strategy was effective [3, 4].

A new brake force control scheme for retrofitted electric vehicles (EVs) was proposed. This scheme allows a conventional anti-lock braking system and a regenerative braking system to be seamlessly integrated with minor modification of the original system and yet provides the braking performance identical to the original braking system. The main idea of this scheme was to maintain the overall braking force to be as close as the driver brake demand by utilizing a unique feature of an anti-lock braking system (ABS). To achieve this during a brake situation, an emulated “Lock” signal was sent to the ABS control unit to decrease the mechanical brake force down until the amount of reduced force was equal to the available regenerative one. Besides, the performance of this retrofitted braking system was evaluated by simulations based on four design aspects, which are energy efficiency, passenger comfort, braking distance, and practicality [5].

Three different cooperative control strategies, namely the maximum-regeneration-efficiency strategy, the good-pedal-feel strategy and the coordination strategy were studied with the aims of regeneration efficiency and brake comfort. Simulations were carried out on models built in MATLAB/Simulink. A real-time brake controller was developed. Road tests under normal deceleration braking and the European driving cycle (ECE) were carried out in a demonstration electric vehicle with the developed regenerative braking system. The results of simulations and road tests showed that the maximum-regeneration-efficiency strategy, which would cause issues in brake comfort and brake safety, could hardly be used with the regenerative braking system adopted. The good-pedal-feel and coordination strategies were advantageous with respect to brake comfort and regeneration efficiency, ensuring the stability and brake safety of the vehicle. The test results of the ECE driving cycle also demonstrated that the improvement in the fuel economy of the electric vehicle enhanced by the regenerative braking system developed was greater than 25% [6].

Regenerative braking is an effective approach for electric vehicles (EVs) to extend their driving range. A fuzzy-logic-based regenerative braking strategy (RBS) integrated with series regenerative braking was to advance the level of energy-savings. From the viewpoint of securing car stability in braking operations, the braking force distribution between the front and rear wheels so as to accord with the ideal distribution curve were considered to prevent vehicles from experiencing wheel lock and slip phenomena during braking. Then, a fuzzy RBS using the driver's braking force command, vehicle speed, battery SOC, battery temperature were designed to determine the distribution between friction braking force and regenerative braking force to improve the energy recuperation efficiency. The experimental results on an “LF620” prototype EV validated the feasibility and effectiveness of regenerative braking and showed that the proposed fuzzy RBS was endowed with good control performance. The maximum driving range of LF620 EV was improved by 25.7% compared with non-RBS conditions [7].

Automated vehicle technology becomes attractive due to its potential applications in automated highways and urban transportation, etc., the coupled and highly nonlinear nature of vehicle dynamic stability control has been challenging, in addition to vision and image processing, trajectory generation and path planning. A combined and integrated control of a four wheel independent drive (4WD) electric vehicle considering longitudinal and lateral dynamics for future automated driving applications has been done, where a new algorithm of the vehicle-level integrated dynamic stability control (VIDSC) is proposed and developed employing four individual wheel torques as target control parameters, and the wheel slip ratios, body slip angle, wheel side slip angles are controlled within the inner feedback loop of the VIDSC algorithm, by adjusting four wheel torque values combined with sophisticated motor control on four sets of in-wheel motors. The results indicate that the integrated approach will help automated guidance control strategy by having efficient and simple architecture of vehicle dynamic control system. Moreover, the controller algorithm has been simulated with dynamic model, and verified the results with experimental vehicle data on constant steering [8].

A new combined brake control strategy (CBCS) for a parallel hybrid electric vehicle was proposed in this study. The CBCS combines a logic threshold control and a fuzzy logic control to ensure the vehicle's longitudinal braking performance, which keeps the wheels from being locked and regenerates more energy effectively. The hydraulic braking system and regenerative braking system are separated in the CBCS control strategy. The agreement of the simulation and experimental results regarding the regenerative ratio and braking performance show that the model of the HEV's braking system and the braking control strategy developed were right. The stability and effectiveness of the braking process control of the proposed control strategy were displayed through the simulation and experimental results [9].

The performance simulation for a hybrid electric vehicle (HEV) equipped with an electro-mechanical brake (EMB) system was conducted. A performance simulator and dynamics models were developed to include such subsystems as the engine, the motor, the battery, an automated manual transmission (AMT), and EMB. The EMB control algorithm that applied the proportional integral derivative (PID) control technique was constructed based on cascade control loops composed of the current, velocity, and force control systems. The simulation results showed that the HEV equipped with an EMB system can regenerate the braking energy by using the proposed regenerative braking control algorithm [10].

The above review has shown that almost the efforts which had been done in this subject were directed towards the studying of the hybrid electric vehicle brake performance and its control for ABS braking system and regenerative braking system separately. Their contributions were limited because in practical case both are generated and ignoring the combination of them. Moreover, the review has established that, there is a need for more investigation on the performance control of the combination of them. Consequently,

there is a general attention to establish more parameters by which their performance parameters have to be established. To achieve this objective, the present work is focused on the establishment of models to simulate of hybrid electric vehicle ABS assisted brake system with regenerative braking system. The simulations have been implemented in the Matlab software, which employs a quarter car's model undergoing a straight line braking maneuver. The simulation also incorporates an electronic hydraulic brake dynamics, continuously variable transmission and road/tire friction. The road/tire friction model is given in the form of an empirical function (Magic formula) describing the nonlinear relation between adhesion coefficient and wheel slip. A PID controller has been implemented with the above model for controlling wheel slip at given desired reference slip value. In addition, the optimal distribution of the power is the kernel part of the real-time control algorithm is used for controlling the regenerative braking system.

2. PARALLEL HYBRID ELECTRIC VEHICLE POWERTRAIN STRUCTURE

Figure 1 shows the structure of the HEV investigated in this paper. The power source of the considered HEV is a 1.4 liter (62 kW) internal combustion engine and a 58 kW electric motor connected to one of the front axis (FWD). The transmission and braking system are a continuously variable transmission (CVT) and an electro hydraulic brake (EHB) system with pedal stroke simulator, respectively. EHB supplies braking torque to all four wheels independently, and the pedal stroke simulator mimics the feeling of the brake pedal on the driver's foot.

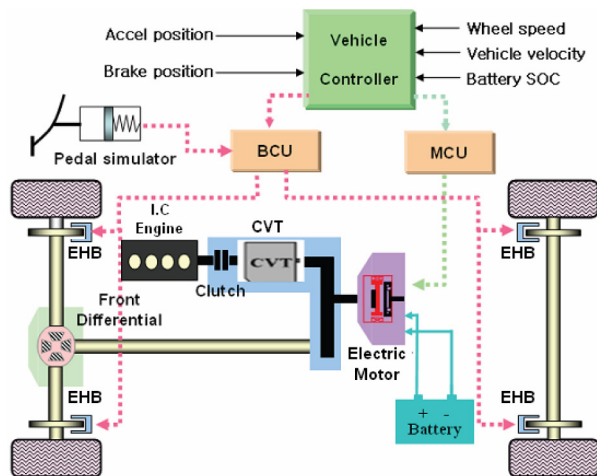


Figure 1. Diagram of the PHEV brake system and electronic hydraulic braking system

The vehicle controller determines the regenerative braking torque and the EHB torque according to various driving conditions such as driver input, vehicle velocity, battery state of charge (SOC), and motor characteristics. The Motor Control Unit (MCU) controls the regenerative braking torque through command signals from the vehicle controller. The Brake Control Unit (BCU) receives input from

the driver via an electronic pedal and stroke simulator, and then transmits the braking command signals to each EHB. This is determined by the regenerative braking control algorithm from the value of remaining braking torque minus the regenerative braking torque. The braking friction torque is generated when the EHB in each wheel creates a suitable braking torque for the motor; the torque is then transmitted through the gear mechanism to the caliper [10].

2.1. Internal Combustion Engine (ICE)

Figure 2 shows the engine characteristic map used in this paper. The complicated characteristics of this engine are due to many factors, such as fuel injection time, ignition time, and combustion process. This study uses an approximated model along with the steady state characteristic curve shown in Figure 2. The dynamics of the engine can be expressed in the following equation:

$$J_e \dot{\omega}_e = T_e(\theta_t \omega_e) - T_{loss} - T_{clutch} \quad (1)$$

Where J_e is the rotational inertia, ω_e is the engine rpm, T_e is the engine torque, T_{loss} is loss in engine torque, and T_{clutch} is the clutch torque.

2.2. Electric Motor

Figure 3 shows the characteristic curve of the 24 kW BLDC motor used in this study. In driving mode, the electric motor is used as an actuator; however, in the regenerative braking mode, it functions as a generator. When the motor is functioning as an actuator, the torque can be approximated using the following 1st order equation:

$$\frac{dT_m}{dt} = \frac{T_{m_desired} - T_m}{\tau_{T_m}} \quad (2)$$

Where T_m is the motor torque, $T_{m_desired}$ is the required torque, and τ_{T_m} is the time constant for the motor.

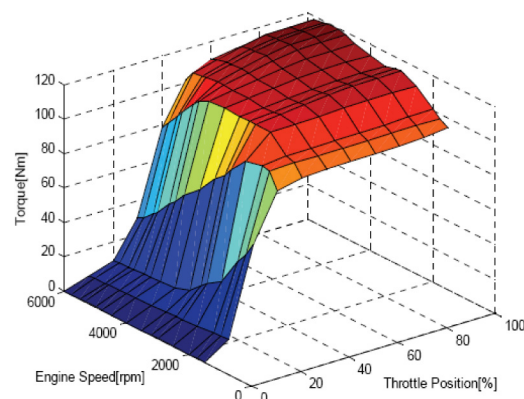


Figure 2. Engine characteristics map

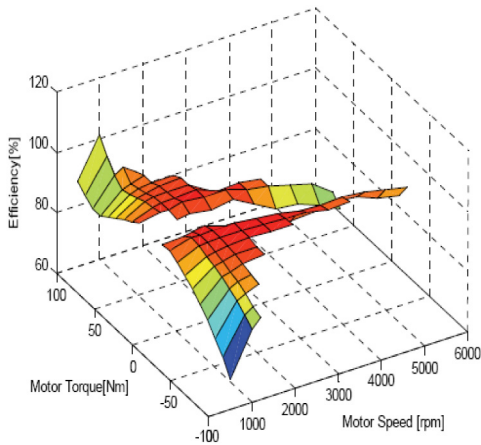


Figure 3. Characteristics map of the electric motor

2.3. Battery

The battery should take into account the relationship between the state of charge (SOC) and its charging characteristics. In this paper, the input/output power and SOC of the battery are calculated using the internal resistance model of the battery. The internal resistance is obtained through experiments on the SOC of the battery.

2.4. Continuously Variable Transmission

The continuously variable transmission (CVT) was modeled to change the gear ratio and rotational inertia that correspond to the transmission's gear position. At Zero Emission Vehicle (ZEV) mode, the electric motor is only actuated when traveling below a critical vehicle speed. In acceleration mode, the power ratio of the motor and the engine is selected in order to meet the demands of the vehicle. At deceleration mode, the regenerative braking torque is produced from the electric motor. The above stated control logic is applied only after considering the SOC of the battery.

2.5. Electronic Hydraulic Brake System

The vehicle type determines that regenerative braking torque can only operate in the driven wheels, which are front wheels in this study. An electronic hydraulic brake system consists of a motor, a pump, an accumulator and a pressure regulating valve as shown in Figure 4. An on-off switch controls the motor work or not to keep the accumulator pressure in a proper scope and also save the electric energy. When a driver depresses the brake pedal, the brake pedal force is transmitted to a master cylinder through a vacuum booster. The master cylinder pressure is supplied to the rear wheels cylinder through a proportional valve. Those are the same as the conventional vehicle. The different is that in the front wheels, a brake control unit (BCU) distributes the regenerative braking torque and friction torque using the brake pedal position, the vehicle velocity (VSS), the maximal charging power and voltage of the battery, CVT gear ratio, and EM speed etc. If the regenerative braking force provided by the EM is not large enough to meet the demand of front wheels braking force, the hydraulic friction brake works simultaneously to supply the insufficient force through the electronic hydraulic brake system. Therefore, the actual front wheels hydraulic pressure calculated by the BCU, which is corresponding to the actual front wheels friction torque, is supplied

by the pressure regulating valve. Because front wheels pressure is supplied from the electronic hydraulic brake system, which makes an unfamiliar brake pedal feeling for the driver compared with that of the conventional brake system without the regenerative braking, a pedal feel simulator is added to consume the brake oil flowing from the master cylinder and simulate the front wheels cylinder characteristics to keep a similar brake pedal feeling.

In the braking system, the braking torque acting on a wheel can be simply defined as:

$$T_b = r_d \cdot \gamma_d \cdot F_b \quad (3)$$

Where T_b is braking torque, r_d is the brake disc radius, F_b is braking force which acts on the disc vertically and γ_d is the brake pad friction coefficient. In the hydraulic brakes, this force can be expressed as

$$F_b = A_p \cdot P_b \quad (4)$$

Where A_p is the brake piston area and P_b is braking pressure generated by the hydraulic fluid. Once the brake disc is fixed, the values of r_d and A_p are constant. One simple equation to represent the hydraulic brake, which is:

$$T_b = \gamma \cdot P_b \quad (5)$$

Notice that, the parameter γ is changing during braking depending on the brake temperature.

In general, the efficiency will increase with the temperature, up to a certain level where fading starts and friction drops rapidly. This means that the anti-lock braking system algorithm needs to be robust to changes in the brake properties [11]. In hydraulic braking, the brake pressure P_b is the control variable, the electronic hydraulic brake system is capable of providing three different control actions, namely

- Increase the brake pressure. In this case the Inlet valve is open and the Outlet one closed;
- Hold the brake pressure. In this case both valves are closed;
- Decrease the brake pressure. In this case the Inlet valve is closed and the Outlet one open.

The hydraulic dynamics model is represented in Figure 5. In this figure, it can be seen that the control variable brake pressure goes through the servo-valve and the pressure flow rate can be controlled by valves, in the end it flows past the hydraulic system and the hydraulic line a transport time delay between the desired and the actual brake pressure. These factors limit the performance of the actuation. Some system identification work of the hydraulic dynamics model have been done in the laboratory [11], they also use a simplify model low pass filter, and the identified results of these two models almost the same, so we can simplify the dynamics into a low pass filter. A rough identification of the characteristics gives: a pure time delay.

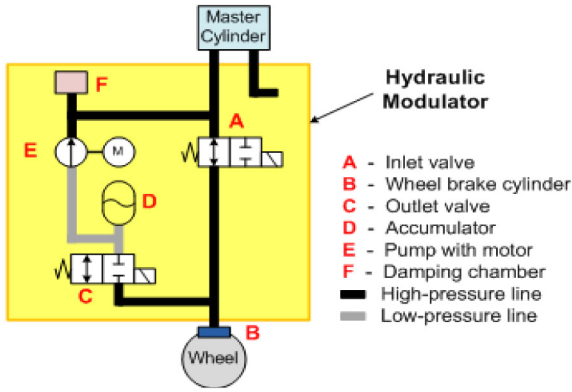


Figure 4. Hydraulic braking system

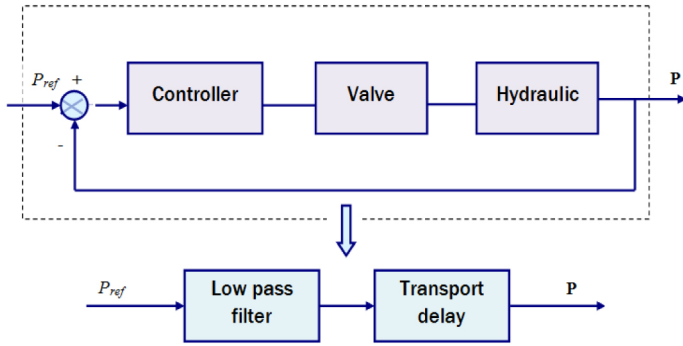


Figure 5. Hydraulic dynamics model

3. VEHICLE BRAKING MATHEMATICAL MODEL

3.1. Wheel Slip Dynamic Model

In this study a simplified quarter car vehicle model undergoing perfectly straight line braking maneuver has been considered as is shown in Figure 6. Thus there is no lateral tire force and also yaw do not exist. Furthermore, the following assumptions are considered in the modelling process:

- There is no steering input.
- Only longitudinal vehicle motion has been considered.
- The sprung mass is assumed to be connected to unsprung mass with a rigid body (no damping effect)
- Approximating the vertical forces as a static value.

The equations of motion are given by:

$$M \ddot{X} = F_x = M \dot{V}_x \quad (6)$$

$$J_w \dot{\omega} = T_m - F_x \cdot R \quad (7)$$

Where V_x represents the longitudinal velocity, F_x is the longitudinal road friction force, J_w is the wheel rotational inertia, ω is the angular rotational speed of wheel, T_m represents the traction torque generated by the motor, R is the wheel radius.

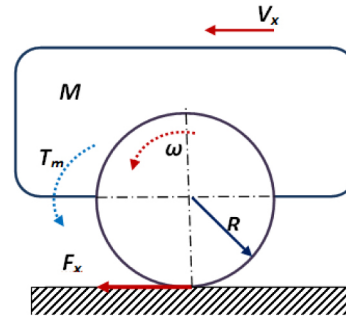


Figure 6. Single wheel's model

Here an important parameter is introduced that is normalized linear wheel deceleration.

It is defined as:

$$\eta = -\frac{\dot{\omega} \cdot R}{g} \quad (8)$$

Observer that η is the linear deceleration of the contact point of the tyre, normalized with respect to the gravitational acceleration g . It is useful since it can be easily and directly compared with the longitudinal body deceleration. By recalling the previous expression of F_x , the following quarter car model is obtained:

$$J_w \dot{\omega} = R F_z \mu \left(\frac{V_x - \omega \cdot R}{V_x} \right) - T_b \quad (9)$$

$$m \dot{V}_x = -F_z \mu \left(\frac{V_x - \omega \cdot R}{V_x} \right) \quad (10)$$

In equations (9) and (10), the state variables are ω and v . Since ω , V_x and λ are linked by an algebraic relationship, it is possible to replace the state variable ω with the state variable λ . This can be simply obtained by plugging the following two relationships:

$$\dot{\lambda} = -\frac{r}{V_x} \dot{\omega} + \frac{r \omega}{V_x^2} \dot{V}_x, \quad \omega = \frac{V_x}{r} (1 - \lambda) \quad (11)$$

into the equations (9) and (10), so obtaining:

$$\dot{\lambda} = -\frac{1}{V_x} \left(\frac{1 - \lambda}{m} + \frac{r^2}{J_w} \right) F_z \mu(\lambda) + \frac{r}{V_x J_w} T_b \quad (12)$$

$$m \dot{V}_x = -F_z \mu(\lambda) \quad (13)$$

It is assumed [12] that the longitudinal dynamics of the vehicle (expressed by the state variable v) is much slower than the rotational dynamics of the wheel (expressed by the state variable λ or ω) due to large differences in inertia. Hence, V_x is considered as a