

Anti-Lock Braking System Control Design on An Integrated-Electro-Hydraulic Braking System

Tianyang Liu, Zhuoping Yu, Lu Xiong, and Wei HAN
Tongji University

ABSTRACT

Two control strategies, safety preferred control and master cylinder oscillation control, were designed for anti-lock braking on a novel integrated-electro-hydraulic braking system (I-EHB) which has only four solenoid valves in its innovative hydraulic control unit (HCU) instead of eight in a traditional one. The main idea of safety preferred control is to reduce the hydraulic pressure provided by the motor in the master cylinder whenever a wheel tends to be locking even if some of the other wheels may need more braking torque. In contrast, regarding master cylinder oscillation control, a sinusoidal signal is given to the motor making the hydraulic pressure in the master cylinder oscillate in certain frequency and amplitude. Hardware-in-the-loop simulations were conducted to verify the effectiveness of the two control strategies mentioned above and to evaluate them. The simulation platform consists of the I-EHB hardware and software including CarSim and MATLAB/Simulink as well as LabVIEW serving as the communication tool. Conclusions can be reached in the light of testing results that both control strategies were able to achieve anti-lock braking under emergency situations. Compared with safety preferred control, master cylinder oscillation control performed better on the functionality of avoiding braking lock and the reduction of braking distance. Also, it is capable of working with electronic stability control systems (ESC) while safety preferred control cannot.

CITATION: Liu, T., Yu, Z., Xiong, L., and HAN, W., "Anti-lock Braking System Control Design on An Integrated-Electro-Hydraulic Braking System," *SAE Int. J. Veh. Dyn., Stab., and NVH* 1(2):2017, doi:10.4271/2017-01-1578.

INTRODUCTION

With the development of new energy vehicles, especially electric vehicles, the technology related to sensors and controllers has been improved dramatically as well, so there are some new demands for braking systems today to leverage the recovery energy during braking. Specifically, in addition to the braking torque provided by the motor, another independent braking system is required to provide the rest of braking torque, which is supposed to be adjustable based on the total braking torque requirement. Also, for the purpose of developing intelligent vehicles, with the help of this braking system whose braking torque can be precisely controlled by digital signals and is adjustable as mentioned above, the design of some other high level features such as automatic emergency braking (AEB) and active cruise control (ACC) etc., will be simpler and more accessible. Therefore, electro-hydraulic braking systems (EHB) are invented and raise more and more attention.

Different from commonly used pump-electro-hydraulic braking systems (P-EHB), the key idea of integrated-electro-hydraulic braking systems (I-EHB) is to integrate the active pressure building device, i.e. the motor in this paper, with the master cylinder in a single shell. So the rotary motion of the motor can be directly transformed into linear movement of the pushrod in the master cylinder using gear transmission systems. By utilizing I-EHB, the size, weight as well as cost of braking systems can be reduced [1]. For instance, one of the famous I-EHB systems, MK C1, which was

produced by Continental AG in 2013, not only achieved the decoupling between the braking pedal and the master cylinder, but also had advantages in size and weight [2].

Anti-lock braking system (ABS) is one of the popular research areas of longitudinal vehicle dynamics, whose function is to prevent wheels from locking during hard braking as well as to keep the slip ratio near the optimal value. Consequently, when ABS works, drivers would not lose control over vehicles and the braking distance can be reduced simultaneously [3].

One common control strategy for ABS is deceleration threshold based algorithm [4]. By comparing the acceleration and deceleration values of wheels detected by wheel speed sensors with the preset thresholds in the control algorithm, the electronic control unit (ECU) commands the solenoid valves in the hydraulic control unit (HCU) to open or close in order to apply, hold or release the brakes, so braking lock can be avoided [5]. Moreover, some researchers took some significant variables during braking into consideration, e.g. road friction coefficient, the initial vehicle speed and so forth, to improve the logic based algorithms [6].

Recently, some advanced control methods have been applied to the ABS controller design, including PID controller [7], sliding-mode control [8], neural network [9] and fuzzy control [10] etc. Most of them are aiming at optimizing the slip ratio.

Tongji University has proposed a novel I-EHB, which has been proved that the system hydraulic pressure can be increased or decreased by sending the motor signals of moving forward or backward with short response time and high reliability. Also, by implementing adaptive PID and chatter-compensation controller, the error of hydraulic pressure in the master cylinder has been reduced to less than 2% compared with the expected value in hardware-in-the-loop simulations [11]. To further ameliorate the system in dimensions and cost, HCU was redesigned by reducing the number of solenoid valves inside it to four instead of twelve in a traditional HCU. As a result, each wheel cylinder with its connected brake is controlled by one corresponding solenoid valve in the new HCU.

Based on the newly improved HCU consisting of only four solenoid valves, two control strategies were designed for ABS, safety preferred control (SPC) and master cylinder oscillation control (MCO). Both strategies have been verified to be effective on a hardware-in-the-loop simulation platform. Finally, testing results were contrasted and analyzed for future work.

STRUCTURE AND WORKING PRINCIPLE OF THE I-EHB

The system structure of the I-EHB applied in this paper is shown in Figure 1.

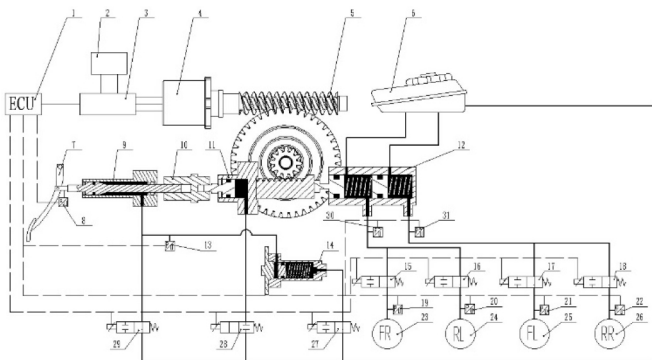


Figure 1. System structure of the I-EHB. The numbers in this figure represent the following. 1-ECU; 2-Battery; 3-DC/AC; 4-Motor; 5-Worm gear transmission; 6-Reservoir; 7-Braking pedal; 8-Pedal displacement sensor; 9-Secondary master cylinder; 10-Adjustment structure; 11-Decoupling cylinder; 12-Master cylinder; 13-Hydraulic pressure sensor; 14-Braking pedal force simulator; 15,16,17,18-Solenoid valves in the HCU; 19,20,21,22-Wheel cylinder hydraulic pressure sensors; 23,24,25,26-Brakes; 27,28,29-Solenoid valves for failure mode; 30,31-Master cylinder hydraulic pressure sensors.

Under the standard working mode, when the driver presses the braking pedal 7, pedal displacement sensor 8 can measure the displacement, transform the information into digital signals and send it to the ECU 1. Then, the ECU computes the desired braking force according to the displacement, and makes the motor 4 rotate by sending out signals through DC/AC 3. Finally, the rotary motion is transformed into pushrod's linear movement through the worm gear transmission system to build the braking hydraulic pressure. At the same time, to ensure the above process works well, the solenoid valve

29 is activated to close, which makes the braking fluid be pressed into the braking pedal force simulator 14 to provide the driver with braking feedback feel. Also, the solenoid valve 28 is activated as well to open, so the movement of the braking pedal 7 is decoupled with the movement of the master cylinder pushrod, which makes it possible that the braking hydraulic pressure is built and controlled by the motor alone.

If there is fault found by the diagnostic system, the control unit will cut off the power supply of the entire system. Consequently, as the solenoid valves 29 and 27 keep open, the braking fluid flows directly into the reservoir 6 when the braking pedal is pressed. And as the solenoid valve 28 keeps close, the connection between the decoupling cylinder 11 and the reservoir is blocked. So under the failure mode, the piston of the secondary cylinder 9 would contact the master cylinder pushrod mechanically, which means that the braking pedal can directly push the piston in the master cylinder to build braking pressure due to the rigidity of the braking fluid. In a word, the I-EHB works in a similar way as a traditional braking system does when it fails.

DESIGN OF THE ABS CONTROL STRATEGIES

The I-EHB is a nonlinear system, and it is pretty difficult to find an approximately equivalent linear system to design control algorithms. What is more, since the I-EHB involves electrical, mechanical and hydraulic subsystems, nonlinear control methods are not applicable either due to the complexity of precisely modeling the system [1]. Therefore, because current task is to verify that the system is able to achieve anti-lock braking based on the new HCU, logic based control strategies such as deceleration threshold based algorithm are more suitable than model-based algorithms as long as they fulfill all demands.

Braking lock is an extremely dangerous situation especially when it occurs to rear wheels, which may result in sideslip. Even if it happens to front wheels, the driver would lose the control of steering. So, to avoid braking lock, based on current I-EHB system and its characteristics, two control strategies were developed, safety preferred control and master cylinder oscillation control.

Safety Preferred Control (SPC)

The braking force of the vehicle depends on the friction torque provided by the brakes, while it is limited by the road friction coefficient. When the braking force exceeds the maximal friction between the tires and the road, braking lock takes place. So to eliminate the tendency of locking, the primary consideration is to reduce the braking hydraulic pressure in wheel cylinders first.

According to the analysis above, the key idea of SPC is to prevent any wheel from locking, which means that if any of the four wheels needs to release its brake, the ECU would command the motor to reduce its output torque, so the hydraulic pressure in the master cylinder would be reduced as well. Details of the SPC strategy are shown in Figure 2.

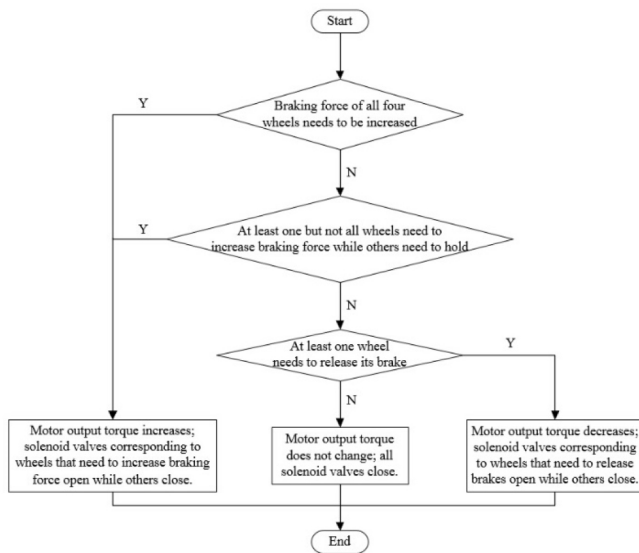


Figure 2. Flow chart of SPC strategy.

Specific situations are processed as follows:

1. If all four brakes need to be released, the ABS proceeds with pressure decrease. The output torque of the motor reduces leading to the reduction of hydraulic pressure in the master cylinder while all four solenoid valves in the HCU keep open.
2. If the braking force of all four wheels needs to be increased, the ABS proceeds with pressure increase. The output torque of the motor increases leading to the increase of hydraulic pressure in the master cylinder while all four solenoid valves in the HCU keep open.
3. If all four brakes need to hold, the ABS proceeds with pressure hold. All four solenoid valves in the HCU keep close.
4. Any of the four brakes needs to be released, the ABS proceeds with pressure decrease. The output torque of the motor reduces leading to the reduction of hydraulic pressure in the master cylinder. At the same time, the solenoid valve responding to the brake which needs to be released opens while others close. So the braking torque of the wheel which tends to be locking decreases while others' remains.
5. At least one but not all wheel needs to increase its braking force while others need to hold, the ABS proceeds with pressure increase. The output torque of the motor increases leading to the increase of hydraulic pressure in the master cylinder. At the same time, the solenoid valve corresponding to the wheel whose braking force needs to be increased opens while others keep close.
6. If variation tendency of the expected hydraulic pressure in a specific wheel is different from the changing tendency of the hydraulic pressure in the master cylinder, the solenoid valve corresponding to that wheel closes.

The calculation of the expected hydraulic pressure values of wheels is based on a modified version of the deceleration threshold based algorithm, which is a popular method applied to most of the commercial ABS due to its simplicity and short response time.

When a vehicle brakes, “the difference between the actual longitudinal velocity at the axle of the wheel and the equivalent rotational velocity of the tire is called longitudinal slip” [3]. The degree of slip can be described by slip ratio as shown in the following equation.

$$\lambda = \frac{v_x - \omega \cdot r}{v_x}$$

where λ is the longitudinal slip ratio; v_x is the longitudinal speed of the vehicle; ω is the angular speed of the wheel and r is the effective radius of the wheel.

Two thresholds, A_1 and A_2 , are preset for the slip ratio. If the actual slip ratio of a wheel is higher than the threshold A_1 , its braking force needs to be reduced. On the contrary, if the actual slip ratio of a wheel is lower than the threshold A_2 , its braking force needs to be increased. The exception is that when the vehicle speed is less than 5 m/s, the ABS is turned off.

According to the SPC strategy, the motor will receive two kinds of signals, which are increasing output torque and decreasing output torque. When the torque needs to be increased, the exact value to be added to the torque depends on the expected hydraulic pressure in the master cylinder, and vice versa. The expected value of the hydraulic pressure in the master cylinder varies according to the road friction coefficient. Based on a large amount of experiments conducted by Tongji University earlier, the error between the expected value of the hydraulic pressure in the master cylinder and the actual value can be limited within 2% using piecewise anti-saturation PID algorithm. The parameters of the PID algorithm are achieved by Taguchi method.

Master Cylinder Oscillation Control (MCO)

There are a few benefits of the SPC strategy such as simple logic, taking fully advantage of the precise pressure control of the master cylinder. However, its main disadvantage is obvious. Due to its conservative, the primary consideration is to prevent any wheel from locking, i.e. to reduce the hydraulic pressure of the whole system even if some wheels may need more braking torque. So, under some circumstances, the vehicle cannot reach its maximal deceleration because of the waste of the tire-road friction force. To improve the braking torque distribution and thus make the slip ratio of each wheel fluctuate around its optimal value, MCO strategy is proposed.

The main idea of MCO is to make the piston in the master cylinder oscillate at fixed frequency and amplitude, so the hydraulic pressure in the master cylinder fluctuates in the same manner. When any brake needs to be released, and at the same time, the hydraulic pressure in its corresponding wheel cylinder is greater than that in the master cylinder, then its corresponding solenoid valve will open. Otherwise, at that time, if the hydraulic pressure in the wheel cylinder is less than that in the master cylinder, its corresponding solenoid valve will close. When any wheel needs more braking force, the working principle is similar. Details of MCO strategy are shown in Figure 3. It is noteworthy that only one wheel's working flow is presented, and others' are similar.