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Comparison of Braking Performance by Electro-Hydraulic ABS and Motor Torque Control for In-wheel Electric Vehicle

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Abstract

In this study, a slip control algorithm using motor torque control during the braking of the in-wheel electric vehicle was proposed and an anti-lock brake system (ABS) simulator was developed on the basis of the test results for electro-hydraulic ABS. The slip control algorithm using motor torque control limits the in-wheel motor torque according to road friction coefficient and slip ratio while the ABS prevents locking of the wheel by lowering or raising the brake pressure through solenoid valve control. A MATLAB/Simulink model and a CarSim vehicle model were developed, and the motor torque control and ABS simulator were applied to the MATLAB/Simulink-CarSim co-simulator and compared braking performance.

Keywords: in-wheel, motor torque control, electro-hydraulic ABS

1 Introduction

In-wheel system installs a motor inside a wheel and directly delivers the driving force of the motor to the wheel [1]. Through the independent control of the in-wheel motor, the in-wheel electric vehicle can implement active safety systems such as traction control system (TCS), anti-lock brake system (ABS), and electronic stability control (ESC) [2]. In conventional vehicles, the active safety control is performed by electro-hydraulic actuator [3]. However an in-wheel electric vehicle does not require additional devices such as hydraulic actuator because it uses the in-wheel motor which has a 10 to 100 times faster response than the hydraulic actuator [4]. Various studies on the in-wheel motor control have been conducted, including the control of the wheel slip to satisfy the optimal slip ratio [5], and the in-wheel motor control by estimating the road friction coefficient [6]. However, the in-wheel motor cannot be used alone in braking due to some limitations such as motor characteristics, battery SOC, etc.

In this study, the braking performance using the in-wheel motor torque control was compared with that of the electro-hydraulic ABS to investigate the advantages and disadvantages of the in-wheel motor torque control. For this purpose, an ABS test environment and an ABS simulator were developed. Performance of the in-wheel and ABS were evaluated through a MATLAB/Simulink-CarSim co-simulator.

2 In-wheel Motor Torque Control

Figure 1 shows the structure of the in-wheel electric vehicle. 35kW in-wheel motors with maximum torque of 75Nm and reduction gear ratio of 8.45 are installed in front, 16kW in-wheel motors with maximum torque of 123Nm and reduction gear ratio of 4 are installed in rear.

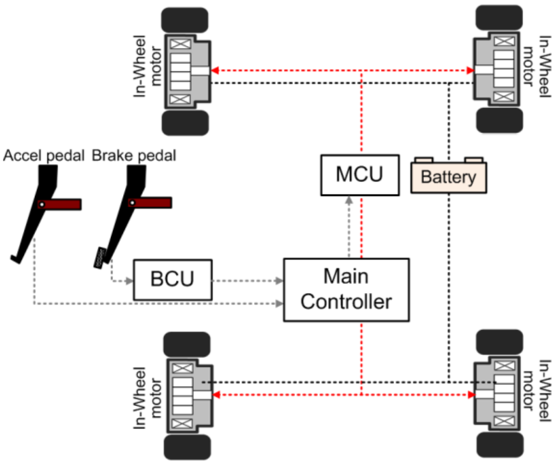

Figure 1: Structure of the in-wheel electric vehicle

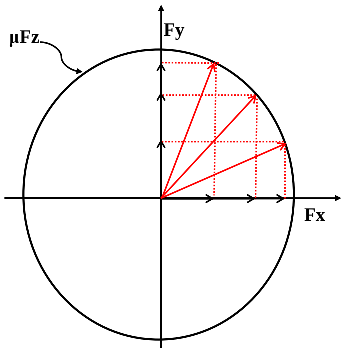

Figure 2: Friction circle

The in-wheel motor torque control is performed based on the friction characteristics between the tire and the road. Figure 2 shows a friction circle. In the friction circle, the vector sum of the lateral force and the longitudinal force must be equal to or less than the product of the normal force and the road friction coefficient, which is summarized as follows:

$$\mu F_z \geq \sqrt{F_x{}^2 + F_y{}^2} \tag{1}$$

In this case, only the force that corresponds to the friction circle is transmitted to the road, and the remaining force spins the wheels. To prevent the generation of a driving or braking force larger than that in the friction circle, Equation (1) is converted to the following driving force limit equation:

$$F_{x\_limit} = \sqrt{(\mu F_z)^2 - F_y{}^2} \tag{2}$$

The motor torque control using only the friction circle, however, cannot guarantee vehicle stability in various driving conditions due to the errors in the estimations of the road friction coefficient, normal force, and lateral force. For improved control performance, a feedback control based on the slip ratio was added. The following equation represents the motor torque limit with the added feedback control [6]:

$$T_{limit} = RF_{x\_limit} + K_{slip\ control}(\lambda_{des} - \lambda_{cal}) \times (\lambda_{cal} > \lambda_{des}) \tag{3}$$

The desired slip ratio (λ_{des}) is defined as the slip ratio that shows maximum friction coefficient in the non-linear tire model in Figure 3 [7].

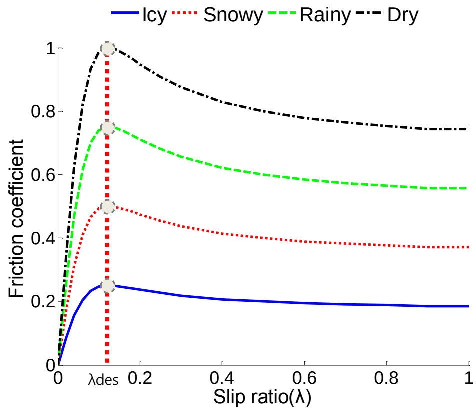

Figure 3: Non-linear tire model (slip ratio vs friction coefficient)

3 ABS Experiment and Simulator

Figure 4 shows the structure of a conventional vehicle with electro-hydraulic ABS. When the driver steps on the brake pedal, pressure is generated in the master cylinder, which is delivered to the cylinder of each wheel through the ABS.

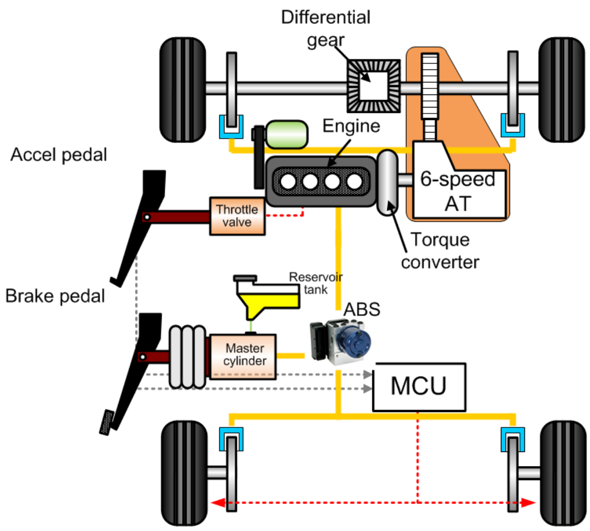

Figure 4: Structure of a conventional vehicle with electro-hydraulic ABS

Figure 5 shows the ABS test environment, which consists of a dSPACE main board, CAN board, AD/DA converter, controller, DC power supply 1, 2, ABS, and a pressure sensor. The solenoid valve of ABS is controlled by the current input of controller, and the motor that plays the role of a pump is controlled by the DC power supply 2.

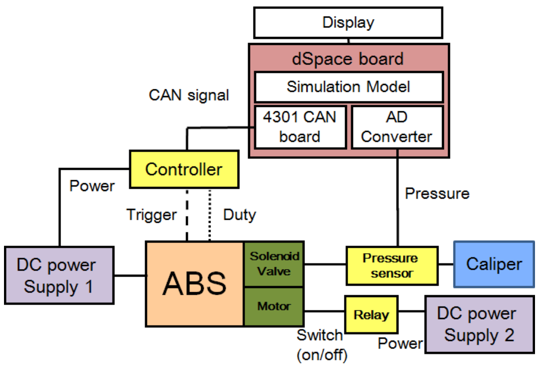

Figure 5: Experimental environments of ABS

Figure 6 shows the ABS simulator. The ABS simulator was modeled based on the ABS test results, considering each solenoid valve and dynamic motor-pump characteristics.

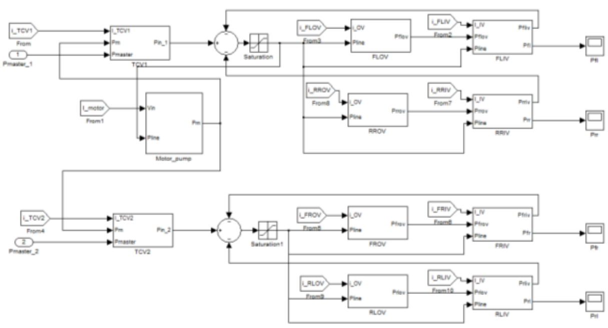

Figure 6: ABS simulator

In Figure 7, ABS test results and simulator results are compared. The solenoid valve was controlled via the current of controller. The ABS system calculates the slip ratio by measuring the wheel speed, and performs the brake pressure control according to the slip ratio to prevent the wheel lock. It is seen from Figure 7 that the simulation results are in close agreement with the test results, which demonstrates the validity of the simulator.

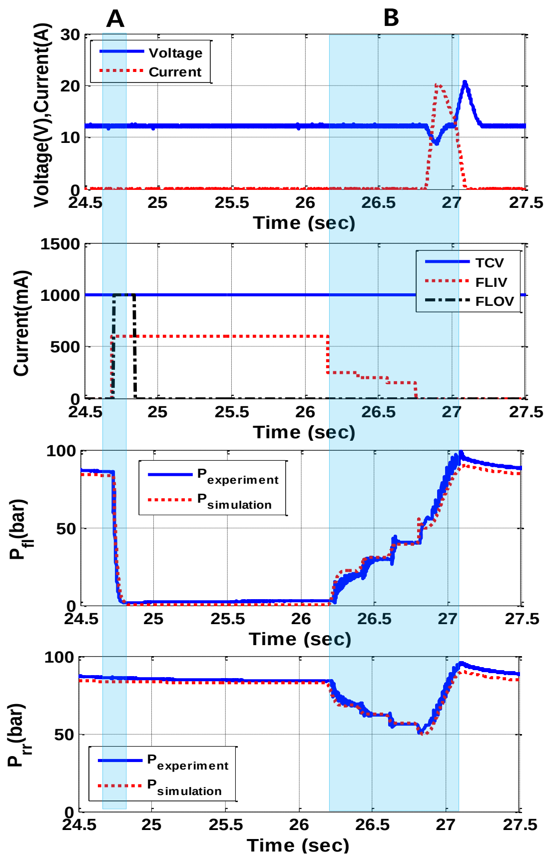

Figure 7: Experimental results

4 Simulation results

Figure 8 shows the co-simulator integrated with the CarSim vehicle model and MATLAB/Simulink model which consists of motor torque controller and ABS simulator. The braking performances of the in-wheel motor torque control and ABS are compared using the co-simulator.

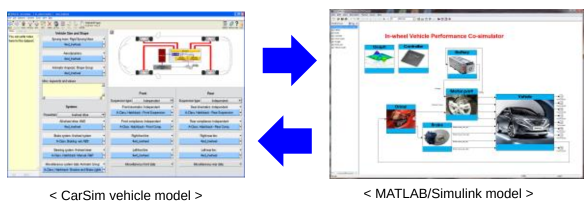

Figure 8: MATLAB/Simulink-CarSim co-simulator

Figure 9 shows the in-wheel motor torque control results when full braking was performed at the initial speed of 60 kph on a road with a road friction coefficient μ = 0.2. The slip ratio was kept at 10% or lower through the in-wheel motor torque control in a section with a vehicle speed of 10 kph or higher, and at 15-20% in a section with a vehicle speed of less than 10 kph. The total braking distance was 64.1 m and the deceleration was maintained around 0.24 g.

vehicle stop section, it was greater than that of the in-wheel motor torque control. It is found that the in-wheel motor torque control showed better braking performance than ABS.

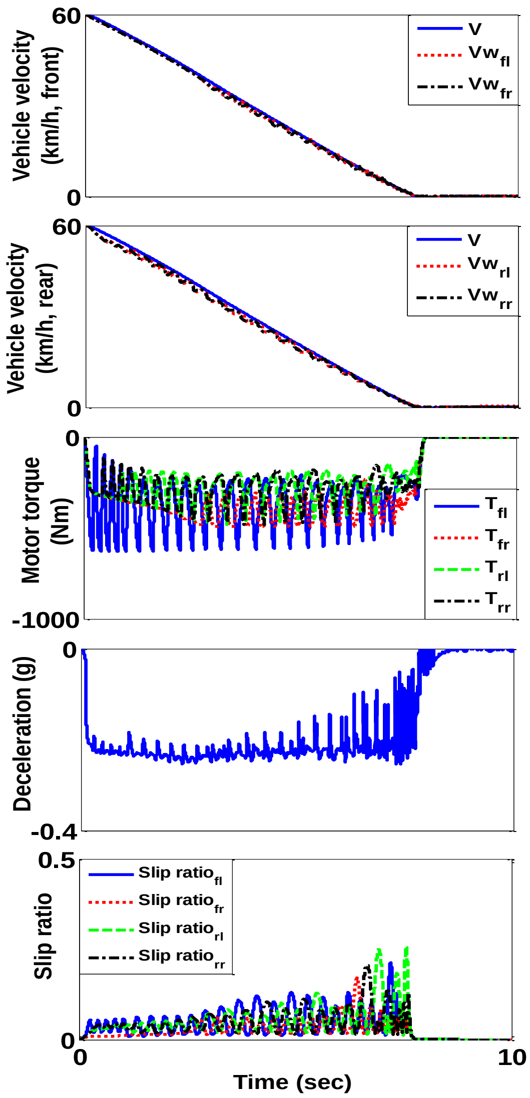

Figure 9: Results of the in-wheel motor torque control, μ=0.2

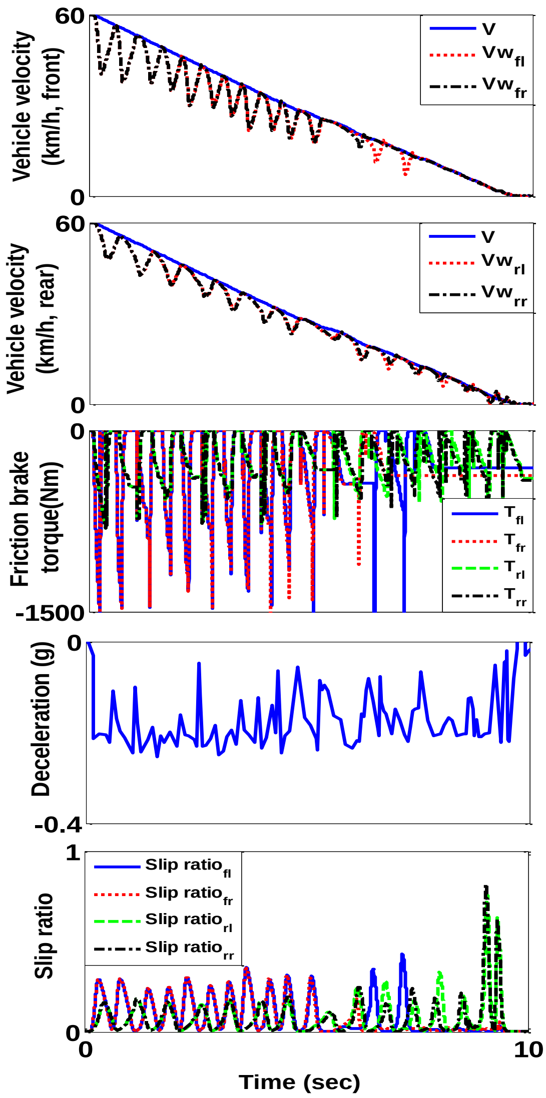

Figure 10: Results of ABS, μ=0.2

Figure 10 shows the results of the control of each wheel pressure using ABS when full braking was performed at the same condition as that in Figure 9. ABS controls the solenoid valve based on the slip ratio and prevents the wheel slip by increasing or decreasing the pressure of each wheel cylinder. However, the total braking distance was 77.7 m, which was longer than that of the in-wheel motor torque control. The deceleration was more variable than the in-wheel motor torque control because of the pressure variation in the wheel cylinder. Although the slip ratio was controlled to 20-25% except in the

Figure 11 shows the in-wheel motor torque control results when full braking was performed at the initial speed of 60 kph on a road with a road friction coefficient μ = 0.4. In the case of the in-wheel motor torque control, the wheel slip did not occur due to insufficient braking force which comes from the in-wheel motor characteristics. The total braking distance was 47.1 m. The braking deceleration was initially 0.27 g because the motor torque was limited by the motor characteristics, but as the speed decreased, the motor torque increased and the maximum deceleration reached 0.35 g.

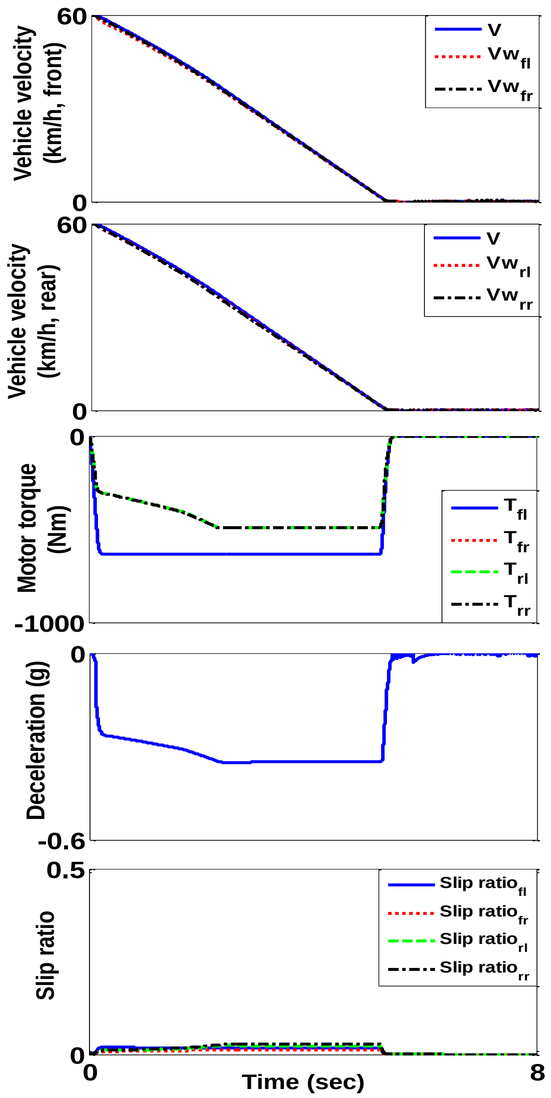

Figure 11: Results of the in-wheel motor torque control, μ=0.4

Figure 12 shows the results of the control of each wheel pressure using ABS when full braking was performed at the same condition as in Figure 11. The ABS results demonstrated that it prevented the wheel slip by increasing or decreasing the pressure of each wheel cylinder according to the slip ratio. The maximum braking deceleration was 0.5 g, and the total braking distance was 39.8 m, which was shorter than that of the in-wheel motor torque control.

It is seen from the simulation results that the in-wheel motor torque control shows better braking performance than ABS in a section where the in-wheel motor provides sufficient braking force, but the desired braking performance cannot be obtained where the braking force of the in-wheel motor is insufficient, that is, where the road friction coefficient is high or for quick braking during high-speed driving. To overcome these limitations, the motor capacity must be increased, but it raises many problems such as higher costs and motor size limits in the wheel. Thus, cooperative control of the in-wheel system and friction braking is required

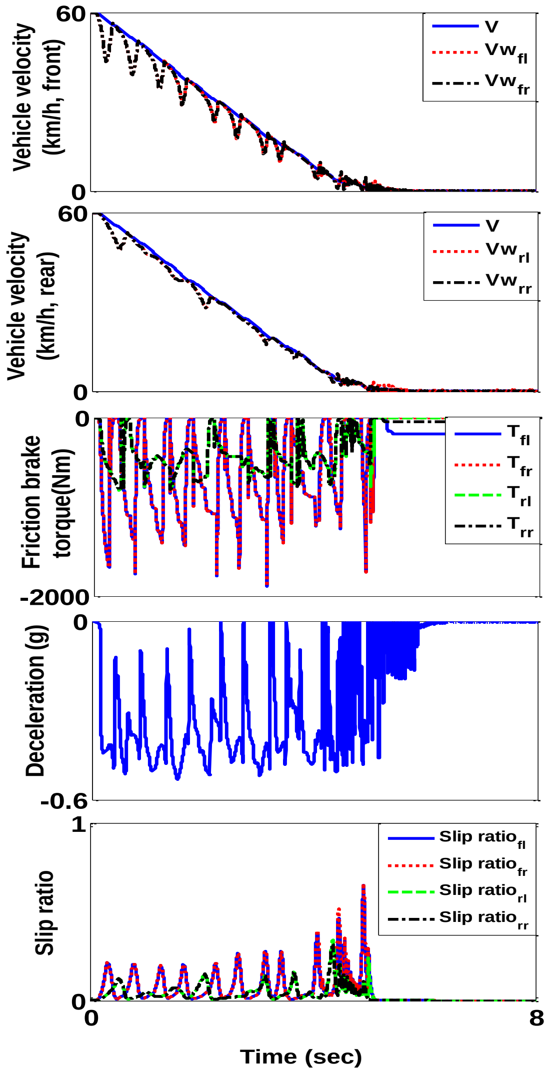

Figure 12: Results of ABS, μ=0.4

5 Conclusions

In this study, braking performance of the in-wheel motor was compared with that of the electro-hydraulic ABS. To implement the ABS operation environment, an ABS simulator was developed based on the ABS test results. The in-wheel motor torque control and ABS simulator were applied to the MATLAB/Simulink-CarSim co-simulator. The simulation results showed that the in-wheel motor torque control showed better performance with a smaller slip ratio and a shorter braking distance compared with the ABS. However, the in-wheel motor torque control may have the problem of