SLIDING MODE CONTROLLER DESIGN FOR OPTIMAL SLIP CONTROL OF ELECTRIC VEHICLES BASED ON FUZZY VEHICLE VELOCITY ESTIMATION LOGIC

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KEYWORDS – Electric vehicles, Driving force observer, Sliding mode control, Vehicle velocity estimation, Acceleration limiter

ABSTRACT - In this paper, a driving force observer based sliding mode controller is designed to achieve optimal wheel slip control for electric vehicles. Sliding mode control techniques have widely been employed in the development of a robust wheel slip controller of conventional internal combustion engine vehicles due to its application effectiveness in nonlinear systems and robustness on model uncertainties and disturbances. A practical slip control system which takes advantage of the features of electric motors is proposed and a novel fuzzy algorithm for vehicle velocity estimation is introduced. The vehicle velocity estimation is based on driving wheel's velocity with acceleration limiters. The simulations and experiments are carried out by an experimental electric vehicle to verify the proposed slip control algorithm and vehicle velocity estimator.

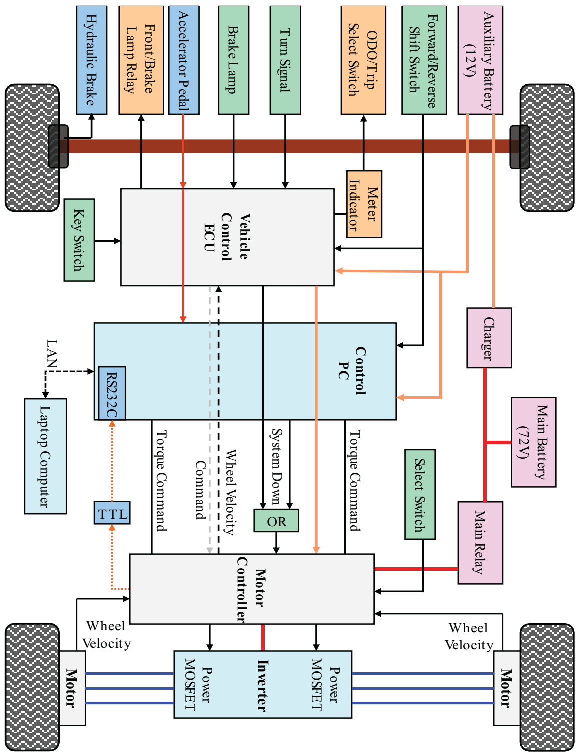
INTRODUCTION

Due to the increasing concerns in environmental-friendly vehicles and electrification of vehicle systems, researches on electric vehicles have been carried out [1],[2]. Especially, in the motion control field of electric vehicles, the longitudinal motion control methods including an anti-slip control [3], a model following control (MFC) based slip control [4] and slip ratio control based on slip estimation were proposed and applied in actual electric vehicles. These novel slip control methods are based on the advantages of electric vehicles equipped with in-wheel motors. Moreover, in order to improve yaw stability of electric vehicles, the various direct yaw moment control methods utilizing independent torque control were proposed by Hiroshi Fujimoto et al.[6],[7]. The advantages of electric vehicles in terms of motion control were summarized as follows [2]:

1) Quick torque generation
2) Easy torque measurement
3) Independent wheel torque control

In this paper, a driving force observer [1] based sliding mode controller is designed to achieve optimal wheel slip control for electric vehicles. The simulations and experiments are carried out by an experimental electric vehicle shown in Fig. 1 to verify the proposed slip control algorithm and vehicle velocity estimator.

(a)



(b)

Fig. 1. Experimental vehicle description: (a) Experimental vehicle-COMS3, (b) Vehicle control system structure

LONGITUDINAL VEHICLE DYNAMICS

Longitudinal vehicle dynamics for controller design

A simple vehicle model appropriate for longitudinal motion control is described as in Fig.2. The simple vehicle model for longitudinal dynamics can be obtained by following assumptions:

b. Vehicle mass is distributed on each wheel equivalently
a. The suspension dynamic is ignored

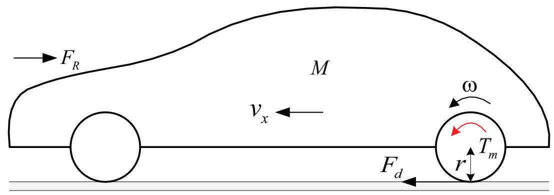


Fig.2. Longitudinal vehicle dynamics

The dynamic equations for the wheel rotating motion and longitudinal vehicle motion are as follows:

$$I_\omega \dot{\omega} = T_m - rF_d \tag{1}$$

$$M\dot{v}_x = F_d - F_R \tag{2}$$

$$v_\omega = r\omega \tag{3}$$

$$F_d = \mu F_z \tag{4}$$

where ω is the wheel angular velocity, T_m is the motor torque, F_d is the driving force, r is the wheel radius, I_ω is the wheel inertia, M is the vehicle mass, F_R is the resistance force including aerodynamic friction force and wheel viscous friction, F_z is the normal force. When a driving motor torque T_m is applied to a pneumatic tire, driving force will be developed at the contact patch between tire and road. At the same time, the tire tread of and within the contact patch is subject to compression during acceleration. The distance the tire travels when it is subject to a driving force will be less than when it is free rotation. This phenomenon is referred to as the wheel slip λ. The wheel slip of a driving wheel is defines as

$$\lambda = \frac{r\omega - v_x}{r\omega} \tag{5}$$

Figure 3 shows the block diagram of proposed wheel slip control system. The control system is composed of a driving force observer, vehicle velocity estimator, and sliding mode controller.

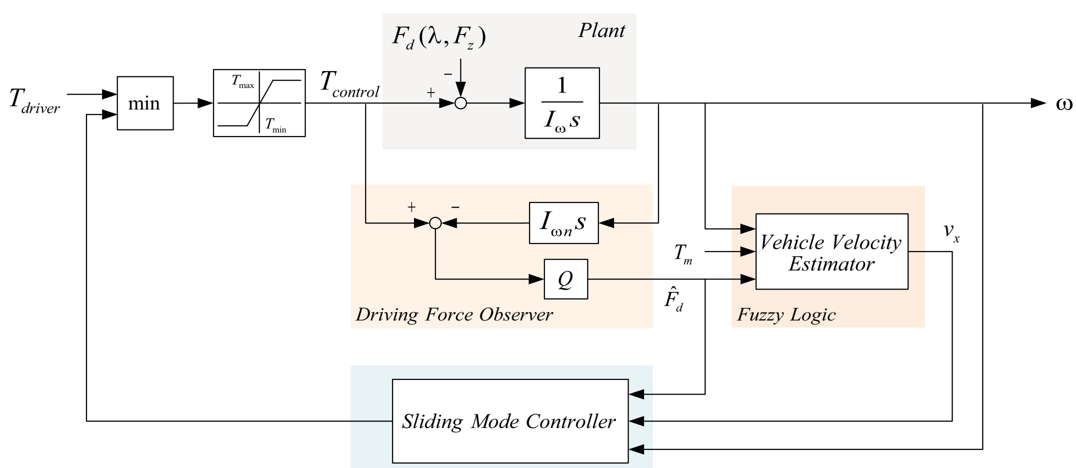


Fig. 3. Structure of proposed control system

The nonlinear wheel slip dynamics is obtained as (6) by differentiating the wheel slip (5) and substituting (1) and (2).

$$\dot{\lambda} = \frac{\dot{v}_x}{v_x}(\lambda - 1) + \frac{v_x}{I_\omega r \omega^2}(T_m - rF_d) \tag{6}$$

WHEEL SLIP CONTROLLER DESIGN

Sliding mode controller design

By continuously controlling wheel slip, we can exactly control the driving force to maximize traction performance. The sliding mode controller [8] discussed in this paper is designed, which is based on nonlinear wheel slip dynamics (6). The relative degree, defined as the number of times the system output must be differentiated to get an explicit input/output relationship, between wheel slip and motor torque control action is one. As usual, define the sliding surface and differentiate it as follows:

$$S(\lambda\ ;\ t) = \left(\frac{d}{dt} + \beta\right)^{n-1} \tilde{\lambda}\ , \qquad \dot{S} = -\beta S = -\beta(\lambda - \lambda_d) \tag{7}$$

Where S is the sliding surface, β is the strictly positive constant gain, $\tilde{\lambda}$ is the tracking error $\lambda - \lambda_d$.
By substituting wheel slip dynamics into the sliding surface equation, the sliding mode control law can be derived as follows:

$$T_m = r\hat{F}_d + \frac{I_\omega \omega \dot{v}_x}{v_x} + \frac{I_\omega r \omega^2}{v_x}\dot{\lambda}_d - \frac{I_\omega r \omega^2}{v_x}\beta(\lambda - \lambda_d) \tag{8}$$

where the feedback gain, β is an only design parameter. In (8), the desired slip ratio, λ_d is difficult to accurately estimate in real-time. The advanced techniques of road surface condition estimation for electric vehicles are proposed [1]. In this paper, the desired slip ratio is chosen 0.01 in high friction road and 0.2 in low friction road, respectively.

Vehicle velocity estimation

In wheel slip control systems, it is necessarily required to detect vehicle velocity to calculate the wheel slip ratio. Hence, the vehicle velocity estimation algorithm based on driving wheel's velocity with an acceleration limiter is proposed.

1. Design of wheel slip indicator

The wheel slip indicator, which is the ratio of the input torque and estimated driving force, is defined as

$$\alpha = \frac{Driving\ Force}{Motor\ Torque\ Input} = \frac{\hat{F}_d}{T_m} \tag{9}$$

where T_m is a driver command torque (i.e., $T_m = T_{driver}$, see Fig.3).
Considering that the vehicle velocity is almost equal to wheel velocity in the adhesive region, the longitudinal wheel motion dynamics (1)-(4) can be idealized in the adhesive region and the transfer function from motor torque input to wheel velocity is given by

$$\frac{\omega(s)}{T_m(s)} = \frac{1}{(I_\omega + Mr^2)s} \tag{10}$$

The maximum wheel slip indicator is calculated in the adhesive region by linear model (10) for slip phenomena [5].

$$\alpha_{\max} = \frac{\hat{F}_d}{T_m} \approx \frac{M\dot{v}_x}{T_m} = \frac{Mrs\omega(s)}{T_m(s)} = \frac{Mrs}{(I_\omega + Mr^2)s} = \frac{Mr}{I_\omega + Mr^2} \quad \text{; in the adhesive region} \tag{11}$$

In the wheel slippery region, (2),(9) are used for calculating slip indicator.

$$\alpha = \frac{1}{r}\left(1 - \frac{I_\omega \dot{\omega}}{T_m}\right) \quad \Rightarrow \quad \dot{\omega} = \left(\frac{1-\alpha r}{I_\omega}\right) T_m \quad \text{; in the slippery region} \tag{12}$$

Using (12) as the basic equation, the recursive least square (RLS) algorithm is applied to identify α in real-time. The algorithm can be formulated as

$$y[k] = \hat{\theta}^T[k]\varphi[k] \tag{13}$$

$$\hat{\theta}[k] = \hat{\theta}[k-1] + L[k]\left(y[k] - \varphi^T[k]\theta^T[k-1]\right) \tag{14}$$

$$L[k] = \frac{P[k-1]\varphi[k]}{\varsigma[k] + \varphi^T[k]P[k-1]\varphi[k]} \tag{15}$$

$$P[k] = \frac{1}{\varsigma[k]}\left(P[k-1] - \frac{P[k-1]\varphi[k]\varphi^T[k]P[k-1]}{\varsigma[k] + \varphi^T[k]P[k-1]\varphi[k]}\right) \tag{16}$$

where $y[k] = \dfrac{\omega[k] - \omega[k-1]}{T_s}$, $\varphi[k] = T_m[k]$, $\hat{\theta}^T[k] = \dfrac{1}{I_\omega}(1 - r\alpha[k])$, $\varsigma[k]$ is the forgetting factor which is chosen as 0.999 in implementation.

2. Wheel acceleration limiter and fuzzy logic

The wheel acceleration limiter is for the purpose of obtaining reference wheel velocity $\tilde{v}_\omega$ which is reasonable wheel velocity for calculating vehicle velocity within physical acceleration limit. Considering that the vehicle acceleration and deceleration limit depend on motor power and vehicle weight, the acceleration limit value $A_{acceleration}$ and deceleration limit value $A_{deceleration}$ are chosen by experimental data (i.e., $A_{acceleration} = 0.24g$, $A_{deceleration} = -0.8g$ on high-μ road). The mathematical expression for the rate limiter is given by

$$A_{deceleration} \le \frac{\tilde{v}_{\omega}[k+1]-\tilde{v}_{\omega}[k]}{T_s} \le A_{acceleration} \tag{17}$$

The structure of rate limiter is shown in Fig. 5.

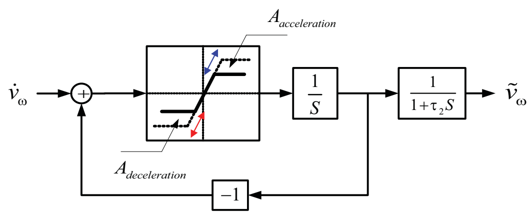


Fig.5. Rate limiter

In order to consider road friction and thereby variation in acceleration limit, the $A_{acceleration}$ and $A_{deceleration}$ are adapted based on simple rule-based fuzzy logic based on the wheel slip indicator and control activation level (CAL), which indicates normalized control torque quantity (i.e., note that the severe slip control occurs in low-µ surface), defined as follows:

$$Control\ activation\ level(CAL) = \frac{T_{driver} - T_{control}}{T_{driver}} \tag{18}$$

$$CAL = \begin{cases} 1 & if\ \ T_{control} = 0\ (severe\ slip\ control) \\ 0 & if\ \ T_{driver} = T_{control}\ \ (no\ slip\ control) \end{cases}$$

In this paper, the fuzzy decision making rule is applied to detect vehicle state and to update the acceleration limit value. Figure 6 shows the fuzzy decision making plot. Since the wheel slip control during acceleration is ultimately considered, the deceleration limit is chosen as a constant value.

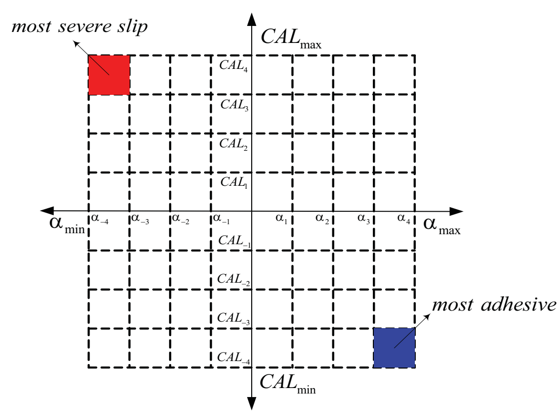


Fig. 6. Fuzzy decision making region for acceleration limit adaptation

Decision rule:

$$\left(\begin{array}{l} Rule:\ \text{IF}\ \ \alpha_i < \alpha < \alpha_{i+1}\ \ \text{AND}\ \ CAL_i < CAL < CAL_{i+1}\ , \\ \qquad\quad \text{THEN}\ \ A_{acceleration} = A(\cdot) \\ where\ \ 0.05g < A(\cdot) < 0.24g\ \ (\text{i.e., g=9.81m/s}^2) \end{array} \right)$$

Finally, the vehicle velocity is calculated by averaging left and right reference velocity ($\tilde{v}_{\omega}$) of two rear wheels.

$$v_x = \frac{\tilde{v}_{\omega,left} + \tilde{v}_{\omega,right}}{2} \tag{19}$$

3. Experimental results for vehicle velocity estimation

In order to verify the estimation performance, the experiments are carried out through an experimental electric vehicle (i.e., COMS3). The driving conditions are as follows:

- Full acceleration with no steer
- Left wheel on high-μ surface
- Right wheel on high-μ/ low-μ/ high-μ transition surface

Figure 6 (a) shows the driving forces from driving force observers. Since the motor torques and wheel acceleration can be easily obtained, it is assured that the estimated driving forces are very accurate. Fig. 6 (b),(c) are experimental results for suggested CAL and wheel slip indicator, respectively.

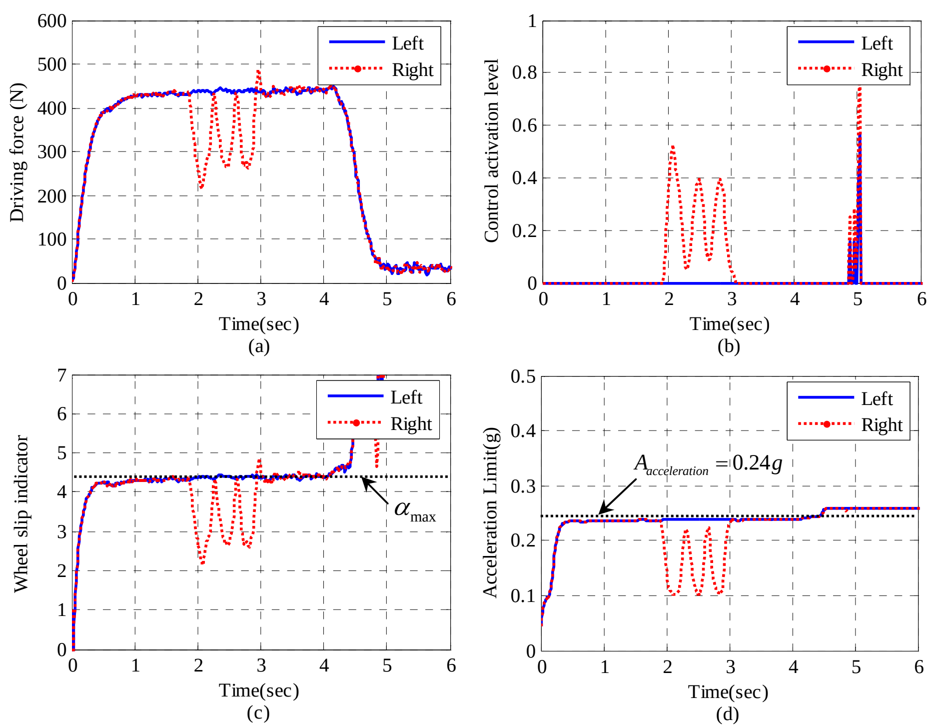


Fig. 6. Experimental results for vehicle velocity estimation: (a) Driving force, (b) Control activation level, (c) Wheel slip indicator (by RLS algorithm), (d) Acceleration limit (by fuzzy logic)

The experimental result for wheel acceleration limit adaptation is shown in Fig. 6 (d). The wheel acceleration limit value for the right wheel, which is with slip control on low-μ surface, is changed in the range of 0.24g.

Figure 7 shows the results for vehicle velocity estimation. As shown in Fig. 7(b), the wheel velocity of right wheel, which is controlled by a sliding controller, slightly oscillates to track the desired wheel slip ratio. In order to use slipped wheel's velocity for estimating vehicle velocity, the slipped wheel's acceleration (i.e., red-thin-line shown in Fig. 7(d)) is processed to dotted line in Fig. 7(d).

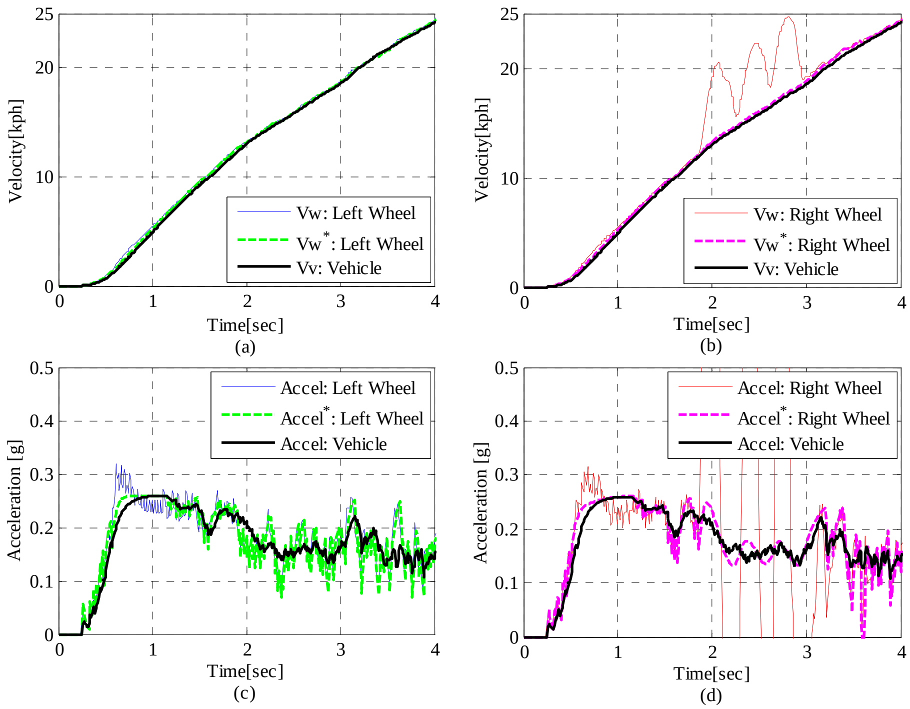


Fig. 7. Experimental results for vehicle velocity estimation: (a) Left wheel velocity, (b) Right wheel velocity, (c) Left wheel acceleration, (d) Right wheel acceleration

SIMULATION AND EXPERIMENTAL RESULTS

The simulations and experimental verification are carried out using CarSim-Matlab softwares and an experimental electric vehicle, COMS3, respectively.

Figure 8 shows the simulation results of proposed wheel slip control implemented in CarSim simulation environment. The road friction is set to 0.2 and desired slip ratio trajectory is given as shown in Fig. 8(b). This simulation results show that the desired slip ratio tracking performance is improved by adjusting a feedback gain β.

Figure 9 (A),(B) are experimental results obtained from an experimental electric vehicle. In this experiment, the slippery road was simulated by an acrylic plate with water. Note that in order to roughly detect absolute vehicle velocity without velocity measuring sensors, the left wheel is driven on asphalt road. Fig. 9(A)-(a) is an experimental result without wheel slip control and Fig. 9(A)-(b)(c) are the results with different feedback gain.

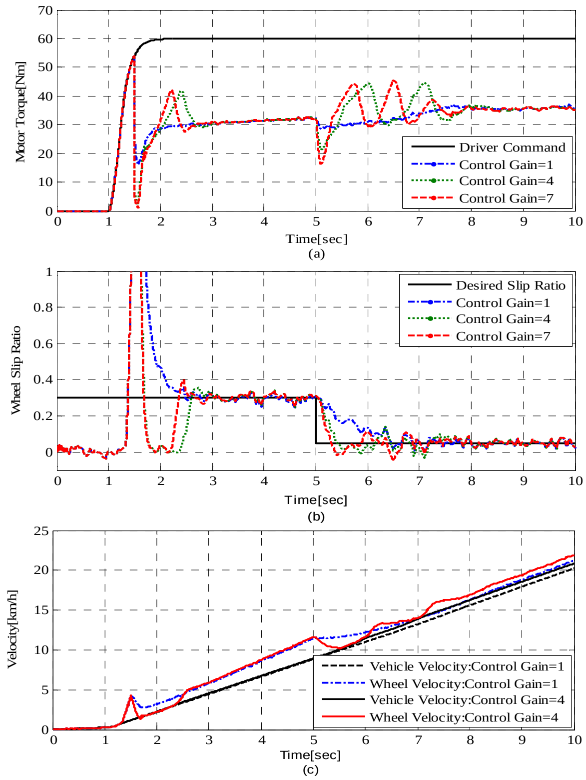


Fig. 8. Simulation results of proposed wheel slip controller (by CarSim): (a) Motor torque, (b) Wheel slip ratio, (c) Velocities of vehicle and wheels

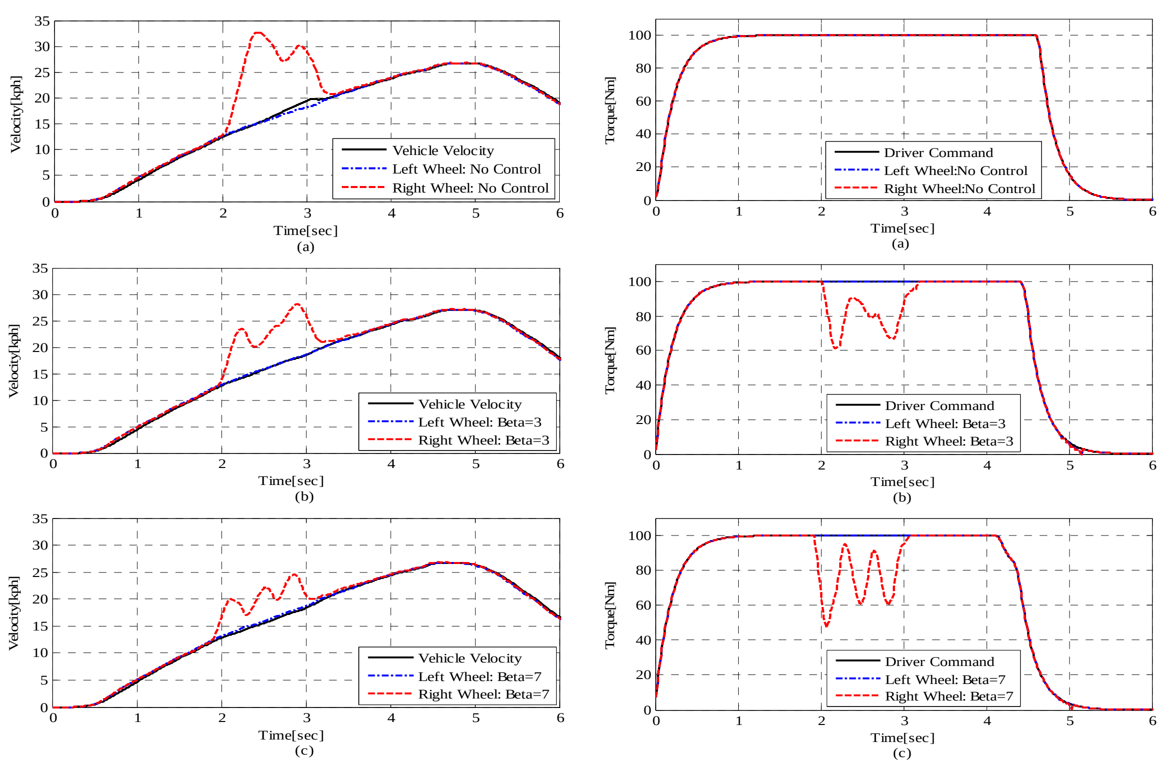


Fig. 9. Experimental results of proposed wheel slip controller (with COMS3): (A) Velocity, (B) Torque

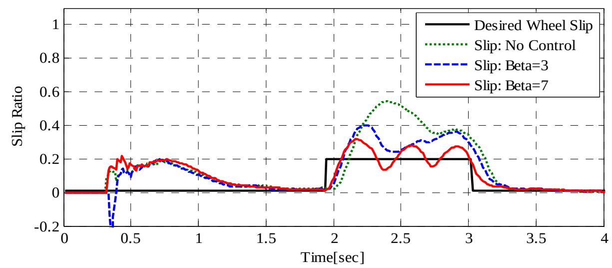


Fig. 10. Experimental results of proposed wheel slip controller (with COMS3): Wheel slip ratio

Figure 10 shows the calculated wheel slip ratios with control and without control. Although there is a slight oscillation in controlled slip ratio due to control motor's pure delay and motor torque saturation, the tracking error converges to zero by increasing feedback gain.

CONCLUSION AND DISCUSSION

The simulations and experiments indicate that a driving force observer based sliding model controller for the wheel slip control works well to track the given desired wheel slip ratio. Compared to the no-control case, estimated vehicle velocity based on two driving wheel's velocities is also close to foreseeable vehicle velocity through the un-slipped wheel's velocity.

REFERENCES

(1) H. Sado, S. Sakai and Y. Hori, "Road Condition Estimation for Traction Control in Electric Vehicle", Publisher, Volume / Issue Number, Page Numbers, Year of Publication (Use 12 point text.)

(2) Yoichi Hori, "Future Vehicle Driven by Electricity and Control- Research on Four-Wheel-Motored "UOT Electric March II," IEEE Trans. on Industrial Electronics, vol. 51, no. 5, pp. 954-962, 2004.

(3) H. Fujimoto, T. Saito and T. Noguchi, "Motion stabilization control of electric vehicle under snowy conditions based on yaw-moment observer," Proc. IEEE Int. Workshop Adv. Motion Control, pp. 35-40, 2004.

(4) Y. Hori, Y. Toyoda, and Y. Tsuruoka, "Traction control of electric vehicle: Basic experimental results using the test EV "UOT electric march"," IEEE Trans. on Industrial Application, vol. 34, pp. 1131-1138, 1998.

(5) S. I. Sakai, H. Sado and Y. Hori, "Motion control in an electric vehicle with 4 independently driven in-wheel motors," IEEE/ASME Trans. Mechatronics, vol. 4, pp. 9-16, 1999.

(6) H. Fujimoto, K. Fujii, and N, Takahashi, "Vehicle stability control of electric vehicle with slip-ratio and cornering stiffness estimation," IEEE/ASME Conference, Advanced intelligent mechatronic, pp. 1-6, 2007.

(7) H. Fujimoto, K. Fujii, and N, Takahashi, "Traction and Yaw-rate Control of Electric Vehicle with Slip-ratio and Cornering Stiffness Estimation," American Control Conference, pp. 5742 - 5747, 2007.

(8) Slotine, J-J. E., and Li, W., Applied Nonlinear Control, Prentice-Hall, 1991.