Torque Control of In-Wheel Motor Electric Vehicles using PI-like Continuous Sliding Mode Method

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ABSTRACT: Traction control plays a crucial role in the safety of vehicles. Therefore, it must have high reliability and robustness. In order to meet such demands, this study proposes a PI-like continuous sliding mode control (PI-CSMC) for the traction control of electric vehicles. First, this paper describes a PI-CSMC and the target vehicle model, which is equipped with in-wheel motors. Second, this paper shows that the wheel slip ratio can be alternatively controlled via wheel speed control. Consequently, the PI-CSMC can be utilized to implement the wheel speed controller. Finally, the slip ratio control is implemented on a real in-wheel-motor vehicle, and experiment of deceleration on slippery surface is demonstrated. The result suggests an effectiveness of the proposed PI-CSMC.

KEY WORDS: electric vehicle, traction control, sliding mode control, slip ratio control

1. INTRODUCTION

Electrified vehicles such as including (plug-in) hybrid electric vehicles and pure electric vehicles (EVs) are more and more developed and produced nowadays. Demands for safe driving are still high and there are room for improvements and subjects to be studied. The traction control of EVs, particularly in-wheel motor EVs (IWM-EVs), is considered to be superior to that of conventional internal combustion vehicles, by exploiting fast torque and wheel speed control of traction motors [1]. However, most of the previous studies have not been focused on the robustness and failure of the actuators. Therefore, this study aims to improve the robustness of the traction control for further safety and redundancy.

Sliding mode control (SMC) is a commonly used non-linear algorithm for various applications, including traction control [2], for its robustness against parameter variations and nonlinearity of the system. In this study, we design a PI-like continuous sliding mode controller (PI-CSMC) based on Super Twisting Algorithm (STA) [3], since the slip ratio dynamics is considered as a first order system [4]. There are some studies that suggest the method to design the optimized parameter for the STA, such as describing function (DF) approach [5,6]. However, while the study [5] assumes a time-invariant first order system for the DF approach, it is suggested by [4] that the slip ratio dynamics is a time-variant system.

In this study, a method to transform a slip ratio control into a wheel speed control while maintaining an equality is shown. In this way, the controller design process will become simpler and previously studied vibration suppression controllers [6] can be integrated, enabling the simultaneous design of slip ratio control and ride comfort control, which will be a future study. As the first step, this study demonstrates an effectiveness of a wheel speed control based PI-CSMC for a slip ratio control of EVs through an experiment using a real IWM-EV. As a benchmark, the proposed PI-CSMC and a simple PI control with pole allocation method is compared on several scenarios; deceleration on a slippery surface without output torque error, with 50ms output delay, and output gain error. The result suggests an effectiveness of the proposed PI-CSMC.

The remainder of this paper is organized as follows. Section 2 describes the vehicle dynamics. Section 3 presents the PI-CSMC and shows the equivalent transformation from a slip ratio control to a wheel speed control. Then, the experimental verification of the slip ratio control based on PI-CSMC based wheel speed control is demonstrated and analyzed in Section 4. Finally, conclusion remarks and the future plan are stated in Section 5.

2. VEHICLE DYNAMICS

We consider vehicle, wheel rotation and longitudinal friction models as shown in Figure 1. The equation of longitudinal motion, wheel rotation, and slip ratio are expressed in the following equations,

$$M\dot{V}_x = \sum_{i=1}^{N} F_{xi} - F_d \tag{1}$$

$$J\dot{\omega}_i = T_i - rF_{xi} \tag{2}$$

$$\lambda_i = \frac{r\omega_i - V_x}{\max\{r\omega_i, V_x, \epsilon\}} \tag{3}$$

where M is the vehicle mass, V_x is the longitudinal vehicle speed, F_{xi} is each wheel's longitudinal force, F_d is the total drag force, J is the wheel inertia, ω_i is each wheel's angular wheel speed, T_i is each wheel's motor torque, λ_i is each wheel's slip ratio, and ϵ is a small constant for avoiding zero division.

Since this study mainly concerns deceleration scenario, we define a new variable y, which is defined by

$$y_i = \frac{r\omega_i - V_x}{V_x} \tag{4}$$

By differentiating (4) and with respect to (1) ~ (3) [4], the slip ratio dynamics on deceleration can be derived as follows:

$$\dot{y}_i = -\left(\frac{\dot{V}_x}{V_x} + \frac{r^2 D_i}{JV_x} + \frac{D_i}{MV_x}\right) y_i + \frac{r}{JV_x} T_i \tag{5}$$

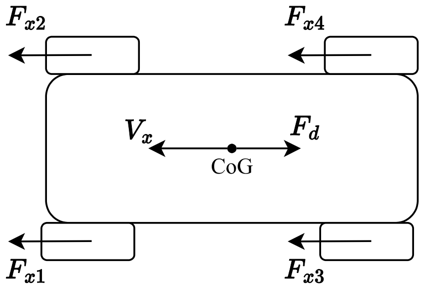
where an approximation $F_{xi} = D_i y_i$ is used and the drag force is neglected for simplification. Here D_i is called driving stiffness. This approximation is valid when we assume the lip ratio is kept within small value, as seen in Fig. 1(c). In (5), $V_x, \dot{V}_x$ and D_i are variables, there, the slip ratio dynamics on deceleration can be classified as a time-variant first order system.

3. SLIP RATIO CONTROL BASED ON SUPER TWISTING ALGPRITHM

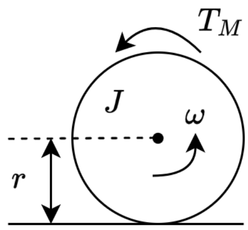
3.1. PI-like Continuous Sliding Mode Controller

A slip ratio control based on Super Twisting Algorithm (STA) [3], which is a PI-like continuous sliding mode control, is represented by

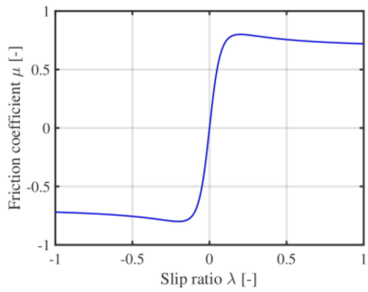
$$T_i = -K_p |y_e|^{\frac{1}{2}} sign(y_e) + \eta$$
$$\dot{\eta} = -K_i sign(y_e) \tag{6}$$



(a) Vehicle body model.



(b) Wheel rotation model.



(c) Longitudinal friction model.

Figure 1: Longitudinal dynamics models.

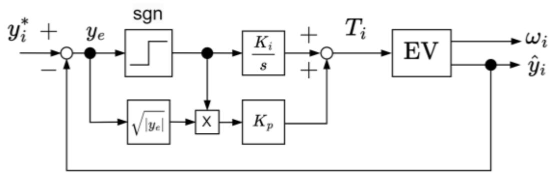


Figure 2: Slip ratio control with PI-CSMC.

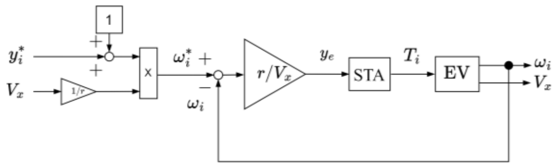


Figure 3: Equivalent wheel speed control with PI-CSMC.

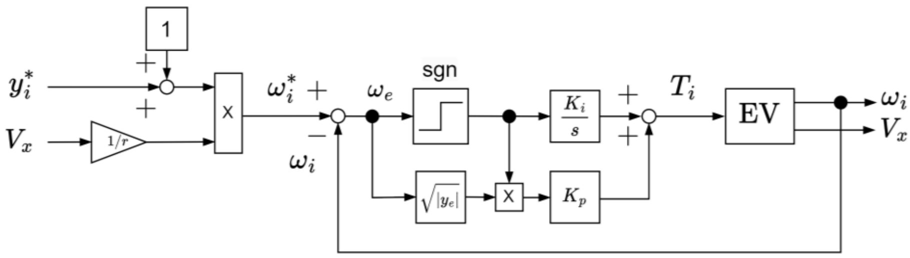


Figure 4: Implemented slip ratio control with PI-CSMC for experimental verification.

where k_P and k_I are the gains of the PI-CSMC for the slip ratio control for the wheel slip dynamics (5), and $y_e = y_i^* - \hat{y}_i$, error between the demand and the estimated values. The block diagram of the slip ratio control with the PI-CSMC is shown in Figure 2.

3.2. Equivalence between "ω control" and "y control"

The slip ratio control (y control) with the PI-CSMC has a complexity with parameter design because of the time-variant nature of the slip ratio dynamics. In order to design a controller in more efficient and straightforward way, an equivalent wheel speed control (ω control) will be derived. From (4), the slip ratio error y_e could be written in another way, hence

$$y_e = y_i^* - \hat{y}_i = y_i^* - \frac{r\omega_i}{V_x} + 1$$
$$= \frac{r}{V_x}\left[\frac{(1+y_i^*)V_x}{r} - \omega_i\right] = \frac{r}{V_x}(\omega_i^* - \omega_i) \qquad (7)$$

This suggests that ω control is basically equal to y control, with a time variant gain r/V_x (see Figure 3). Therefore, if y control has adaptive gains proportional to the vehicle speed V_x, it is equivalent to ω control. In this study, ω control has constant gains and it is assumed that the adaptive gain V_x/r will be added on future studies. Thus, the actual slip ratio control with the PI-CSMC for later experimental verification is shown in Figure 4.

The speed control system in Figure 4 has an input of wheel angular speed ω and the output of motor torque T_i. In this case, an apparent vehicle model for the controller design becomes time invariant and given by $\frac{1}{J_{wf}s}$. In this way, previous studies dedicated to the vibration suppression of the longitudinal motion (often modeled with wheel (angular) speed dynamics such as in a study by [8], for example) can be integrated easier with ω control. Furthermore, the structure of the slip ratio control with the PI-CSMC in Figure 4 can be straightforwardly integrated into a driving force control (DFC) or the upper layer controllers [9].

4. EXPERIMENT

4.1 Experimental setup

An experimental verification of the slip ratio control with PI-CSMC using a real IWM-EV was carried out. The slip ratio controller was created on a Matlab/Simulink environment and implemented to AutoBox (PPC 750GX 1 GHz, 32GB SDRAM program memory, 96MB SDRAM data storage). Torque control and measurements are executed at 10 KHz frequency. Figure 5 shows the configuration of the experimental vehicle system. A PC is used for setting controller gains, selection of controllers and data acquisition through ControlDesk software.

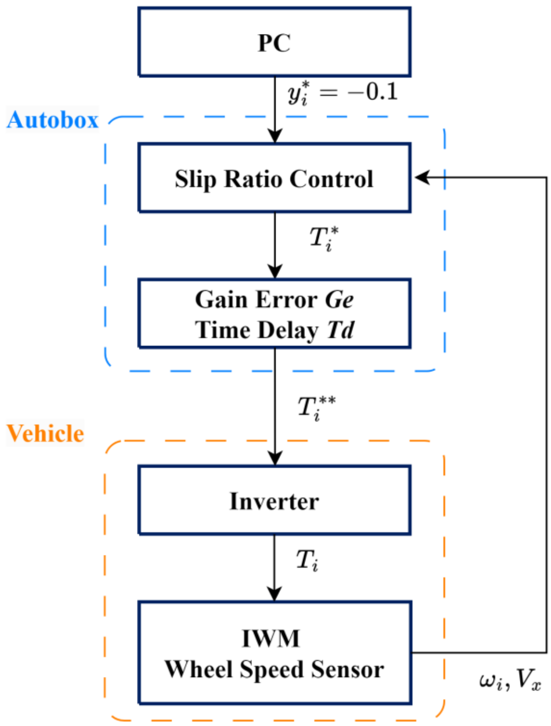


Figure 5: Vehicle control architecture.

Figure 6: Experimental vehicle FPEV-2 Kanon and slippery wet sheets for a deceleration experiment. The vehicle enters the slippery surface at 5 m/s and decelerated using front IWMs with the slip ratio demand of $y_i^* = -0.1$.

Table 1: Vehicle and controller parameters.

Parameters	Value
Vehicle Mass M	925 kg
Wheel radius r	0.302 m
Wheel inertia J	1.24 kg · m^2
Friction coefficient μ	0.2 ~ 0.3
Initial vehicle speed	5 m/s
PI-CSMC gains K_p, K_i	100, 200
Conv. PI gains K_{p-PI}, K_{i-PI} and poles	37.2, 279 -15 rad/s
Slip ratio demand y_i^*	-0.1

The experimental EV and the experimental setup are shown in Figure 6 and Table 1. The wet polymer sheets are used to emulate a slippery surface with friction coefficient around 0.2 ~ 0.3. The vehicle entered the slippery surface at 5 m/s and decelerated using front IWMs with the slip ratio reference of $y_i^* = -0.1$. The rear wheels are not driven but used as a vehicle speed sensor, so that the accurate slip ratio can be obtained.

In addition to the PI-CSMC, a conventional PI (Conv-PI) is also implemented as a benchmark. The gains of Conv-PI are determined by a pole allocation, with a wheel speed dynamics model of $G_w = \frac{1}{J_{wf}s}$. In order to evaluate the robustness of the controller, artificial gain error G_e and time delay T_d are introduced to the torque command. For each controller, 4 cases are demonstrated; no gain error and no time delay, 50 ms time delay, gain error by 0.5 (under actuation), and gain error by 1.5 (over actuation). These errors reflect accumulative time delays and partial actuator failure scenarios, as simple yet worst case

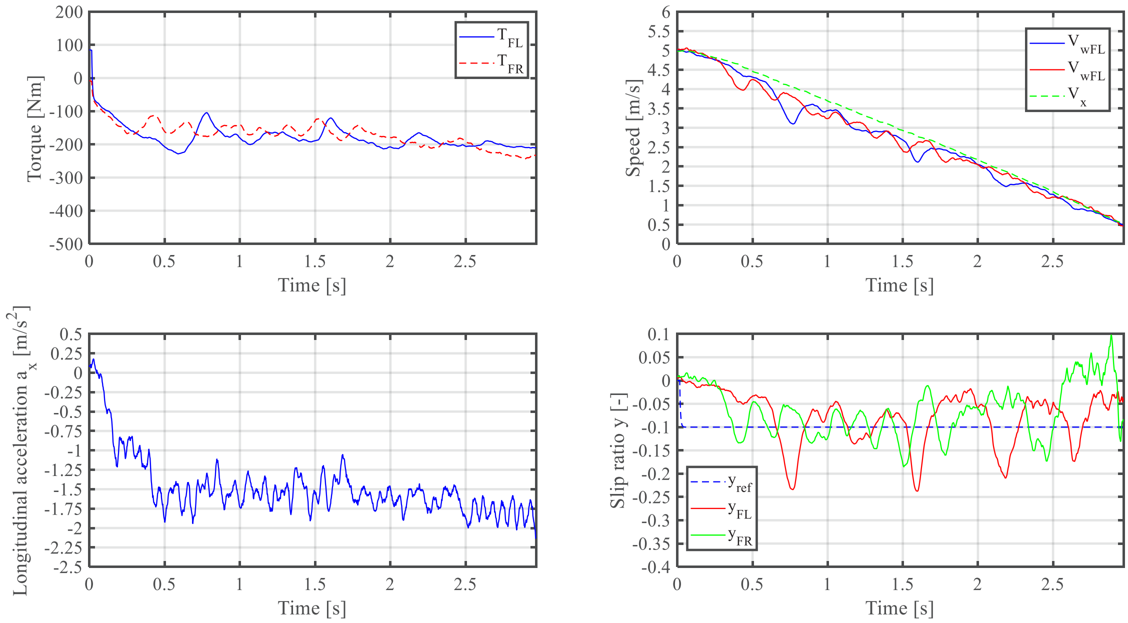


Figure 7: Deceleration with conventional PI without command signal delay or actuator error (conventional).

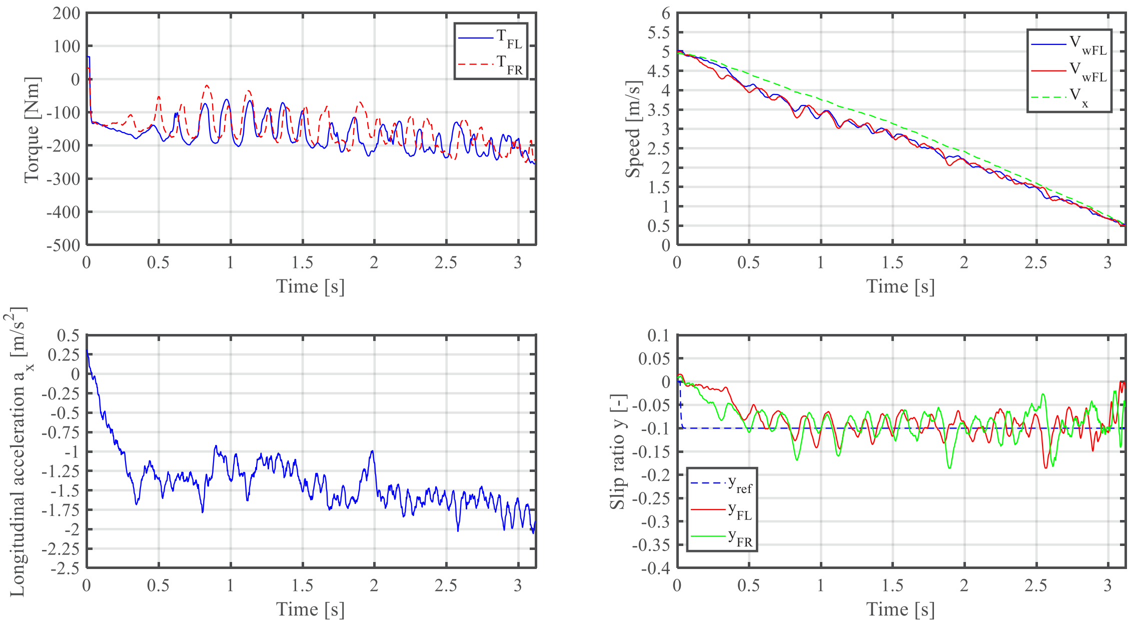


Figure 8: Deceleration with PI-CSMC without command signal delay or actuator error (proposed).

scenarios, considering typical electronic control units are run at 10 ms sampling period. The controller gains are determined when the controller remains stable with these time delay and actuator gain errors.

4.2 Experimental results

Figures 7 to 14 show the result of the deceleration tests with the conventional PI and proposed PI-CSMC. In the figures, the top left waveform is the motor torque demand T_i^* (it should be noted that it is not the final output T_i^*after giving artificial actuator gain error or delays), the top right is the vehicle body speed V_x and wheel speed V_w, bottom left is the longitudinal acceleration a_x and bottom right is the slip ratio demand y_{ref} and measured values y_i. Table 2 shows performance indicators of the experiments. As the indicators, root-mean-square error $y_{e-\mathrm{RMS}}$, maximum undershoot $y_{\mathrm{US-max}}$, and maximum overshoot $y_{\mathrm{OS-max}}$ are shown (these are the average of left and right wheels). Having smaller values on these indicators means better performance of the slip ratio control. For PI-CSMC, which is the proposed method, percentile improvements with respect to Conv-PI are also shown. These three indicators are calculated between the beginning of the deceleration and the time when vehicle speed reaches to 0.5 m/s.

In the case of without delay or actuator gain error, the proposed PI-CSMC has clearly better slip ratio control compared to the Conv-PI (Figure 7 and 8). While the slip ratio of the Conv-PI often exceeds above -0.05 and below -0.2, that of PI-CSMC stays within it. The improvement is also suggested on the three indicators in Table 2, with at least 20% reduction in each indicator. The torque input of the PI-CSMC has more fluctuations than Conv-PI, leading to the improvement of the slip ratio control.

In the case of with time delay of 50 ms (see Figs. 9 and 10), both controllers have larger fluctuations than without the time delay. Particularly the PI-SCMC has greater deterioration, even $y_{e-\mathrm{RMS}}$ of PI-SCMC is slightly larger than Conv-PI by 0.2%, but the other two indicators $y_{\mathrm{US-max}}$ and $y_{\mathrm{OS-max}}$ are reduced by 5.1% and 20.8% respectively. Therefore, it is still suggested that PI-SCMC has better performance with the time delay of 50 ms.

In the case of under-actuated scenario, with actuator gain error 1.5, (see Figs. 11 and 12), both controllers have lower slip ratio than the previous cases. It takes 1~2 seconds to reach the slip ratio bellow the demand value of -0.1. Even after that, the slip ratio tends to stay lower than the demand value. However, also suggested in Table 2, the three performance indicators of the PI-CSMC $y_{e-\mathrm{RMS}}$, $y_{\mathrm{US-max}}$ and $y_{\mathrm{OS-max}}$ are lower than those of Conv-PI, by 16.2%, 13.6% and 15.5%, respectively.

Table 2 Performance indicators

Cases	$y_{e-\mathrm{RMS}}$	$y_{\mathrm{US-max}}$	$y_{\mathrm{OS-max}}$
Conv-PI (no error)	0.0623	-0.1114	0.1523
PI-CSMC (no error)	0.0378 -39.3%	-0.0859 -22.9%	0.1138 -25.3%
Conv-PI (T_d = 50ms)	0.0888	-0.3452	0.1540
PI-CSMC (T_d = 50ms)	0.0890 +0.2%	-0.3276 -5.1%	0.1219 -20.8%
Conv-PI ($G_e = 0.5$)	0.0697	-0.0698	0.1257
PI-CSMC ($G_e = 0.5$)	0.0584 -16.2%	-0.0603 -13.6%	0.1062 -15.5%
Conv-PI ($G_e = 1.5$)	0.0521	-0.1110	0.0355
PI-CSMC ($G_e = 1.5$)	0.0396 -24.0%	-0.1209 +8.9%	0.1040 -23.2%

In the case of over-actuated scenario, with actuator gain error 1.5, (see Figs. 13 and 14), due to the increased output gain, the rise time become smaller than the other three cases. While PI-CSMC behaved mostly in the same manner as in the case with no delay or gain error, the Conv-PI has larger torque adjustments than the other cases, and achieves lower $y_{e-\mathrm{RMS}}$ compared to the case with no delay or gain error. Still it is clear that PI-CSMC has larger torque adjustments and smaller slip ratio tracking error compared to Conv-PI, achieving 24% smaller $y_{e-\mathrm{RMS}}$.

4.3 Discussion on future prospects

The experimental results demonstrated that the proposed PI-CSMC has overall better slip ratio control performance. However, there are still some rooms for improvements in performance, parameter design and stability analysis. Further systematic parameter determination and tuning, in other words, the adaptation of DF approach with simplified yet comprehensive dynamic model including outer loop (slip ratio loop) will be the next first step. This study assumed a delay and actuator gain error on the torque output, but other scenarios, such as sensor measurement delay, should be considered in the future work in order to improve the fault-safety and redundancy of the system.

Another direction will be to integrate other control strategies, such as vibration suppression controls, to further improve the ride comfort while maintaining slip ratio control performance. Also, more detailed comparisons with other slip ratio controllers, such as integral SMC, linear quadratic controller [4], should be carried out as well.

5. CONCLUSION

This study proposed a slip ratio control based on a PI-like continuous sliding mode control (PI-CSMC) for a traction control of electric vehicles (EVs). To simplify a controller design, then an equivalence of a slip ratio control and wheel speed control was shown, and time invariant wheel speed control architecture was adopted for PI-CSMC. Experimental verification of the slip ratio control of PI-CSMC using a real EV was carried out on several cases including the presence of time delay and gain error in the system and overall improvements, in terms of slip ratio control performance, from a conventional PI based slip ratio control were confirmed. Systematic parameter design, further stability and fail-safety analysis, and integration of ride comfort control strategies will be carried out in the future.

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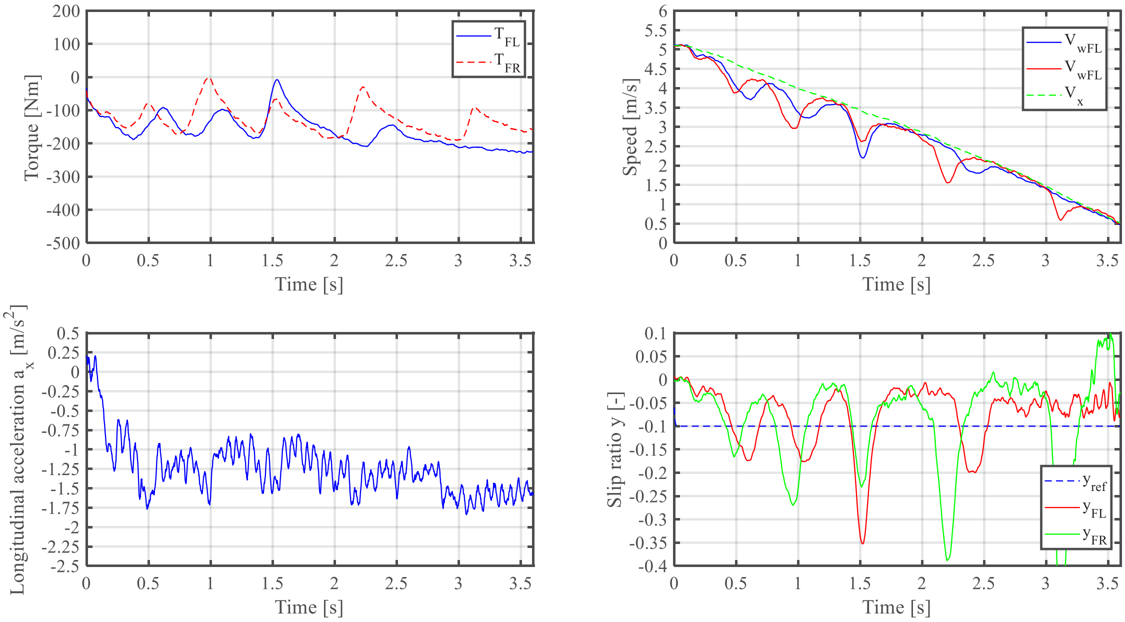

Figure 9: Deceleration with conventional PI with command signal delay T_d = 50ms (conventional).

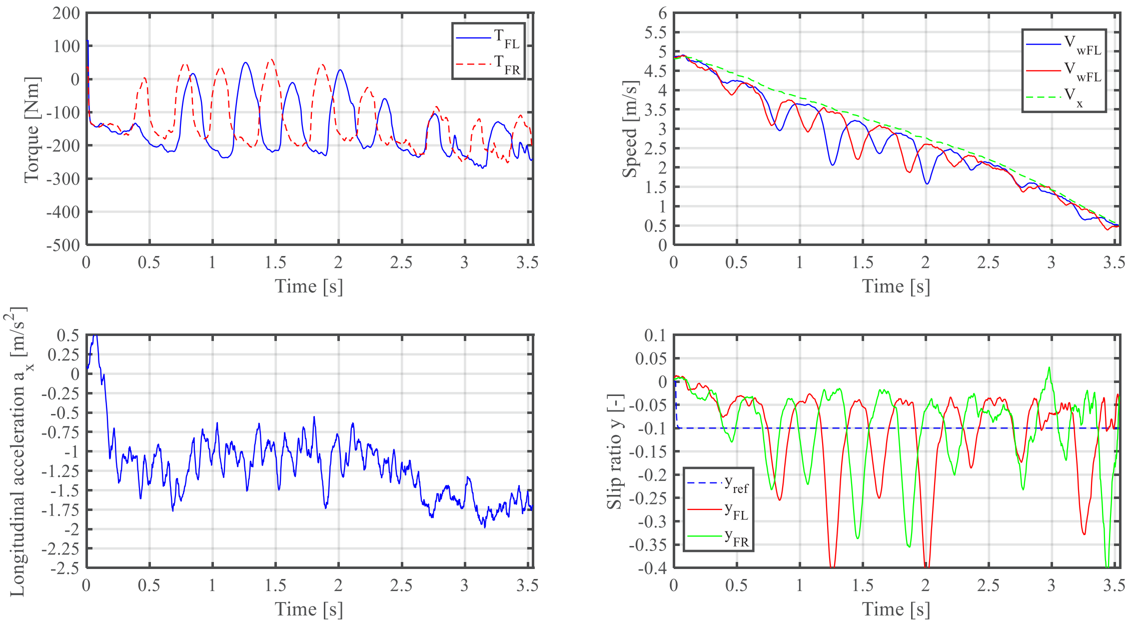

Figure 10: Deceleration with PI-CSMC with command signal delay T_d = 50ms (proposed).

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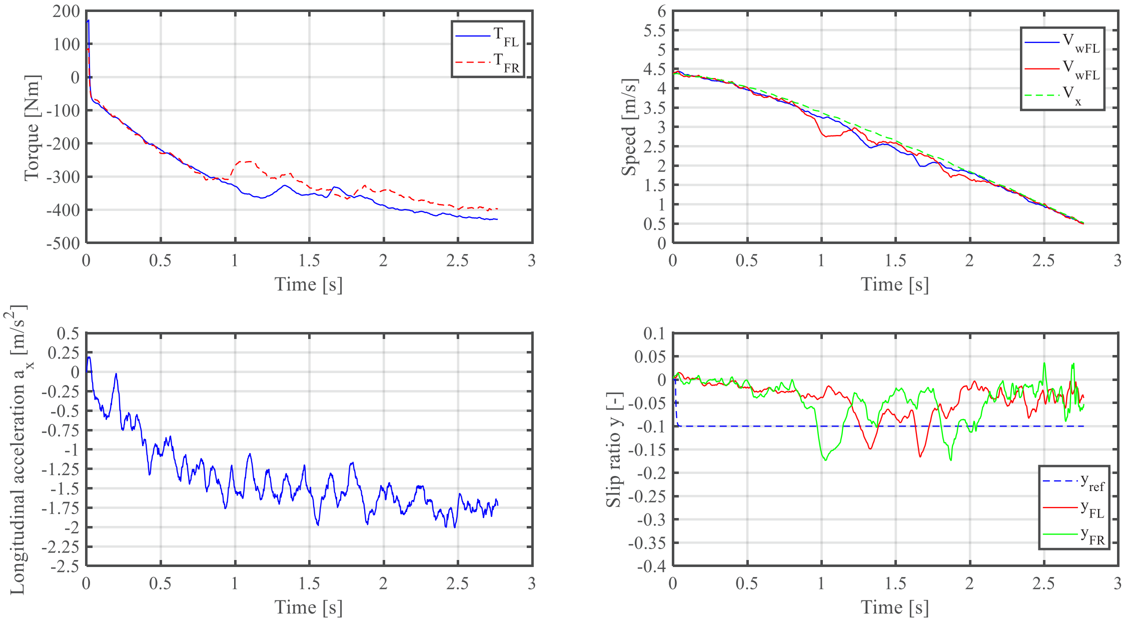

Figure 11: Deceleration with conventional PI with actuator gain error $G_e = 0.5$ (conventional).

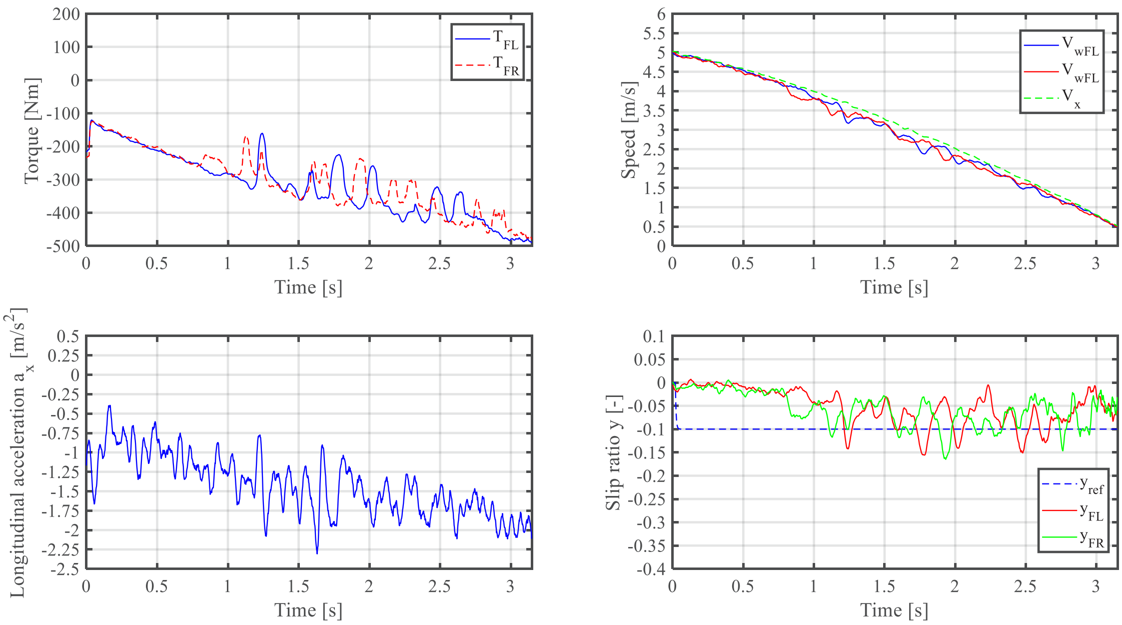

Figure. 12: Deceleration with PI-CSMC with actuator gain error $G_e = 0.5$ (proposed).

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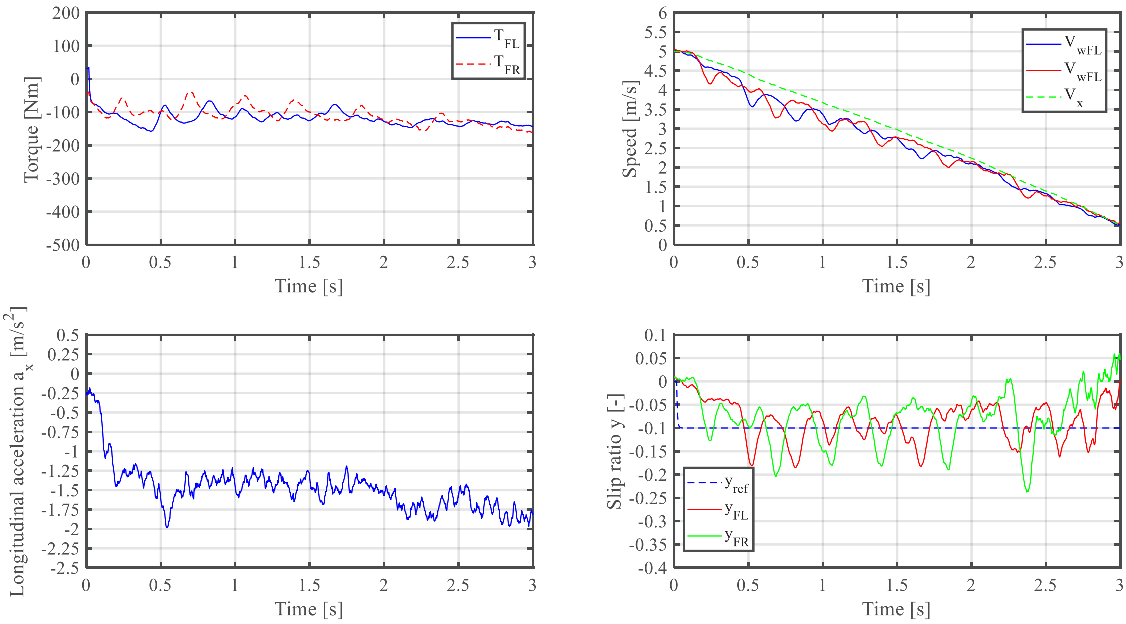

Figure 13: Deceleration with conventional PI with actuator gain error $G_e = 1.5$ (conventional).

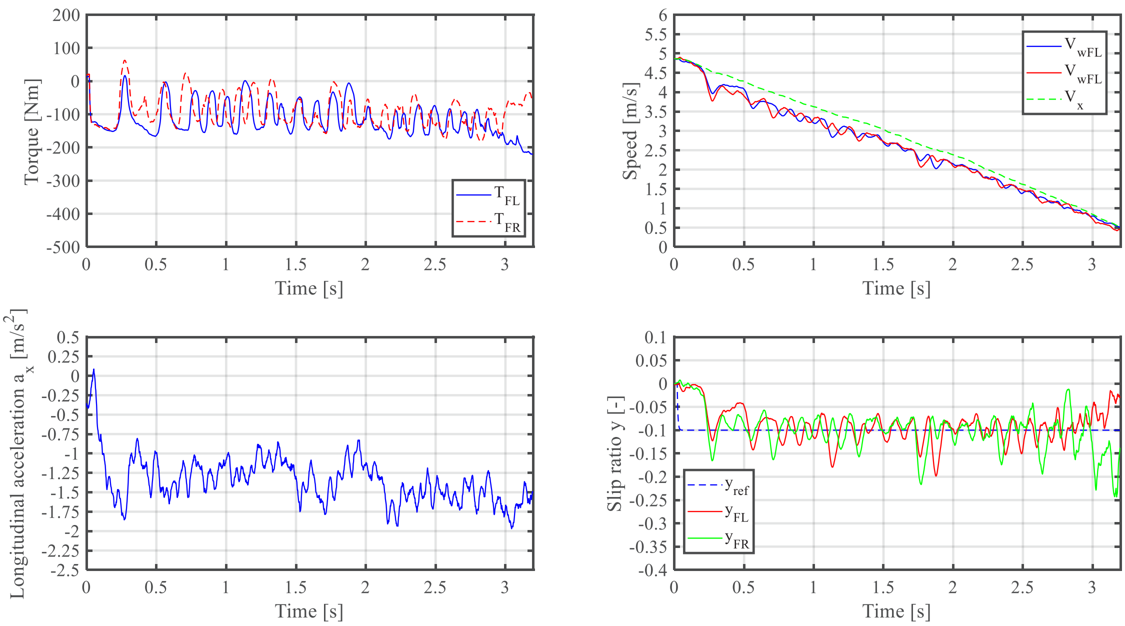

Figure 14: Deceleration with PI-CSMC with actuator gain error $G_e = 1.5$ (proposed).