36th International Electric Vehicle Symposium and Exhibition (EVS36)
Sacramento, California, USA, June 11-14, 2023

Traction Control using Disturbance Observer in Hybrid Electric Vehicles

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Executive Summary

This paper presents a disturbance observer (DOB) based traction controller in hybrid electric vehicle. A proposed control scheme estimates disturbance in a specific frequency range caused by wheel slip, neither chassis velocity nor road conditions, and reduces driving force in accordance with the estimated disturbance. In order to extract the disturbance in specific frequency range causing wheel slip, a band pass filter is employed to the DOB. In addition, proportional-integral type regulator is applied to reject the disturbance effectively. To validate the proposed control algorithm, vehicle test is performed. The validation results show that the proposed controller achieves superior anti-slip performance compare to the conventional controller.

Keywords: HEV (hybrid electric vehicle), traction control, disturbance observer

1 Introduction

In the case of hybrid electric vehicles (HEV), high acceleration performance can be provided when a vehicle launch due to the characteristics of motor with high initial torque or additional power with internal combustion engine (ICE). However, due to these characteristics, wheel slip may occur during vehicle start-up, which may cause driveline vibration and unnecessary power loss [1]. Therefore, HEV require more accurate and frequent wheel slip reduction control compared to existing ICE vehicles.

In the case of conventional ICE vehicles, a traction control system (TCS) has been used to solve wheel slip problems. Based on the vehicle velocity, TSC determines wheel slip when excessive slip speed occurs and solves the problem by reducing torque. In the case of HEV, wheel slip can be prevented before TCS is activated, unlike conventional ICE vehicles, by using the characteristics of the motor with fast response.

In order to be applied to control software of mass-produced vehicles, it is necessary to reduce the complexity of the control structure compared to previous studies and further consider wheel slip characteristics. Therefore, in this paper, the DOB-type traction controller is proposed that is very simple and stronger for wheel slip compared to the conventional studies. The proposed controller consists of a disturbance estimator and a torque compensator. The disturbance estimator extracts disturbances of a specific frequency associated with wheel slip. In order to minimize the effects of disturbance such as road resistance or vehicle weight, the relative low frequency component of disturbance must be removed. Moreover, high frequency noise must also be removed. Therefore, instead of the low pass filter (LPF) used in the conventional DOB structure, a band pass filter (BPF) is applied to the disturbance estimator. The torque compensator changes the driving demand torque according to the estimated disturbance. PI type torque compensator is proposed to eliminate steady-state errors regardless of road surface conditions.

The following sections describe the overall scheme of the proposed DOB based traction control algorithm and are organized as follows. A nominal plant model is derived for the controller design in Section 2. The DOB based traction control algorithm is described in Section 3. In Section 4, the performance of the proposed algorithm is validated by vehicle experiments. Section 5 provides a conclusion of this study.

2 Control Oriented Vehicle Model

Assuming that the driving train, lateral, yawing, pitch and roll dynamics are neglected, and the vehicle mass is uniformly distributed [1], the longitudinal vehicle model is expressed by Newton's 2nd law as

$$m\dot{v} = F_{drive} - F_d \tag{1}$$

where m is the vehicle mass, v is the longitudinal vehicle velocity, F_{drive} is total tire force. F_d is vehicle load such as aerodynamic drag force F_{areo}, rolling resistance F_{roll} and the gravitational force $mgsin\theta$ by road grade as the following

$$F_d = F_{areo} + F_{roll} + mgsin\theta \tag{2}$$

The dynamic equation of rotational wheel motion is given as

$$J_{whl}\dot{\omega} = T_{dmd} - R_{eff}F_{drive} \tag{3}$$

where J_{whl} is the wheel moment of inertia, ω is the wheel angular velocity, T_{dmd} is the total driving torque considering the engine and the motor, and R_{eff} is the effective radius of a tire.

The wheel slip is defined the relative difference between a driving wheel's rotational speed and the free-rolling vehicle speed [2], and the slip ratio λ is defined as

$$\lambda = \frac{R_{eff}\omega - v}{R_{eff}\omega},\ R_{eff}\omega > v \tag{4}$$

Fig. 1 shows the typical relation curve between the tire-road friction coefficient and the slip ratio.

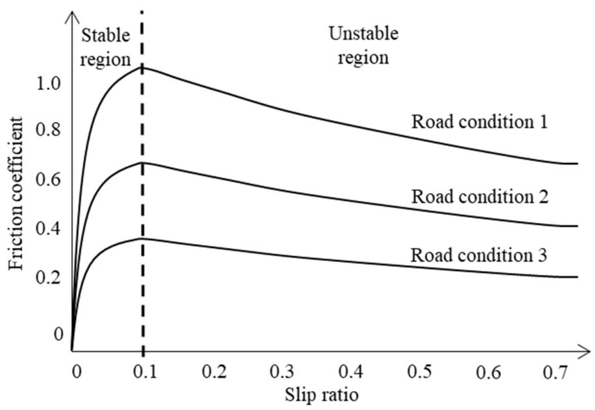

Figure 1: Typical relation curves between tire-road friction coefficient and slip ratio

The coefficient of friction is affected by road conditions and slip ratio, and the tire can be driven stably when the tire is in a specific slip ratio range. In this paper, only the angular velocity of the driving wheel is used for traction control without any chassis velocity. Thus, the vehicle can be regarded as one-inertial system based on a driving wheel with an equivalent moment of inertia, it is expressed as

$$J_{eq} = J_{whl} + mR_{eff}^2(1 - \lambda) \tag{5}$$

where J_{eq} is the equivalent inertia moment of the vehicle at the driving wheel.

In order to maintain the slip ratio within the stable region, desired λ is set to 0, the nominal inertia moment of the vehicle is given as

$$J_n = J_{whl} + mR_{eff}^2 \quad (6)$$

The wheel angular acceleration of one-inertial system is calculated as

$$J_n\dot{\omega} = T_{dmd} - F_d R_{eff} \quad (7)$$

where $F_d R_{eff}$ is external disturbance, that is unknown.

Finally, the transfer function of the nominal plant model is given as

$$G_n(s) = \frac{\omega(s)}{T_{dmd}} = \frac{1}{J_n s} \quad (8)$$

The nominal inertia moment of the vehicle J_n can be obtained from vehicle experiments. Based on the data during acceleration of the vehicle under high friction road, a linear regression technique is employed to identify the parameter of the nominal system G_n.

Fig. 2 shows the comparison of experimental result and estimated plant model. It has equivalent behavior in time domain response. Thus, it is shown that the nominal plant model can be replaced the actual system.

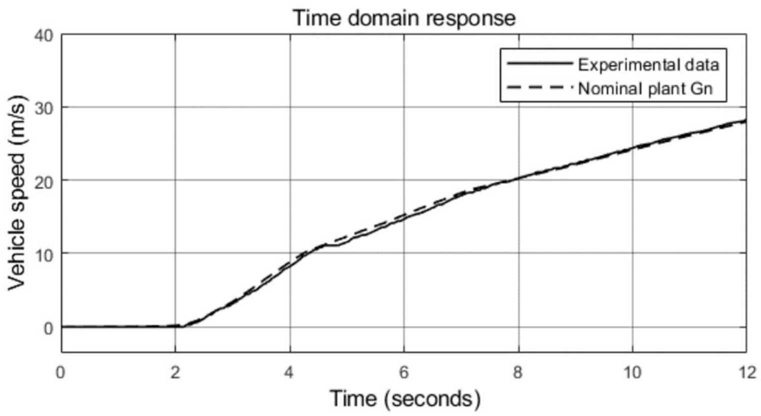

Figure 2: Comparison of experimental result and nominal plant model

3 Design of Traction Control System Based on DOB Framework

3.1 Overview of Proposed Traction Control

In this section, the design of the proposed traction controller for HEVs is presented.

The proposed traction controller prevent severe wheel slip without any chassis velocity, reducing vibration and energy waste with a simple structure. Fig. 3 shows a block diagram of the proposed control algorithm which consists of two parts: the DOB-based disturbance estimator and the PI-type torque compensator. [3]

3.2 Design of Disturbance Estimator

The disturbance that causes wheel slip of the vehicle is estimated by the disturbance estimator and the estimated disturbance $\hat{d}$ is as follows.

$$\hat{d} = Q(s)\{(G(s)G_n^{-1}(s) - 1)u + G(s)G_n^{-1}(s)d\} \quad (9)$$

If the nominal plant $G_n(s)$ is closed to the actual plant $G(s)$, that is $G(s)G_n^{-1}(s) \approx 1$, then Equation (9) is as follows.

$$\hat{d} \approx Q(s)d \quad (10)$$

If the low-pass filter $Q(s)$ is designed with a sufficiently small time constant, i.e. $Q(s) \approx 1$, then the estimated disturbance $\hat{d}$ is similar to the actual disturbance d. The more proof of the DOB is shown at the previous studies in [5]

The disturbance $\hat{d}$ estimated using a traditional DOB includes all vehicle loads within a wide frequency range, depending on the time constant of $Q(s)$. Therefore, if the traditional DOB is used, the vehicle compensates wide frequency range of disturbance to the driving demand torque regardless of the type of load. That is, the vehicle performs same behavior according to the driving torque demand regardless of any disturbance. However, the desired behavior of the vehicle in this study is to estimate only the wheel slip as a disturbance and compensate only for it.

Disturbances associated with wheel slip have a relatively high frequency range. However, disturbances associated with load slope and air drag have a relatively low frequency range. In previous studies, high pass filter (HPF) is employed to remove an effect of relatively low frequency range of road load [4]. However, it is vulnerable to the system noise. Thus, it is necessary to employ additional signal processing to minimize the noise effect. In this paper, to effectively estimate wheel slip and also minimize the effects of system noise, the following BPF is applied [6].

$$H(s) = \frac{2\omega_c s}{s^2 + 2\omega_c s + \omega_c^2} \tag{11}$$

where, ω_c is the central frequency of BPF and is set to coincide the frequency when wheel slip occurs. Finally the disturbance $\hat{d}$ can be expressed as

$$\hat{d} \approx H(s)d \tag{12}$$

3.3 Design of Torque Compensator

In order to control wheel slip, the drive demand torque is compensated based on the disturbance estimated from the DOB, which is the model error of a specific frequency range between the actual plant and the nominal plant. The structure of the torque compensator is shown in Fig. 3. In the proposed control algorithm, the following proportional-integral(PI) regulator is applied.

$$u_{pi} = -(K_p + \frac{K_i}{s + K_f})\hat{d} \tag{13}$$

where, K_p, K_i and K_f are P-gain, I-gain and forgetting factor.

In addition, the compensation range of the driving demand torque is implemented as a type of dead-zone in consideration of the sign and magnitude of the disturbance which is not sensitive but is good for wheel slip prevention. Moreover, the change rate of compensation torque is limited by the rate limiter to prevent shock and vibration issues.

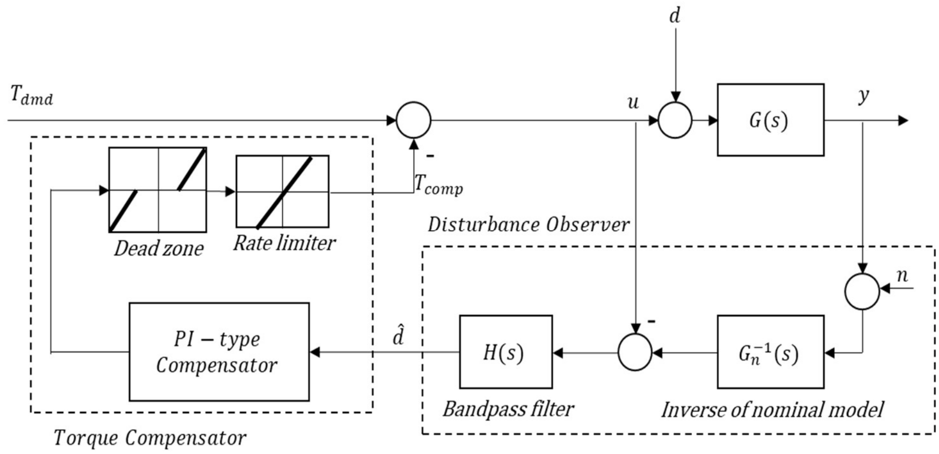

Figure 3: Block diagram of proposed traction control system

4 Vehicle Test and Result

In this section, experimental results are presented to demonstrate the practical feasibility of the proposed traction control system.

4.1 Experimental environment

The test vehicle is C-segment SUV with the pre-transmission parallel hybrid electric vehicle (HEV) configuration. The vehicle test has been performed in the test track at Hyundai/Kia Namyang R&D center proving ground for acceleration according to the road conditions.

In order to show the superior performance of the proposed control algorithm, it is compared with a conventional DOB based control algorithm with HPF and control not applied. Control parameters of each controller are chosen to have equivalent performance on a high friction flat load. Control parameters of the conventional DOB controller are set that proportional error gain K_p is 200 and time constant of HPF τ is 0.1. Control parameters of the proposed controller are set that proportional error gain K_p is 100, integral error gain K_i is 0.12, forgetting factor K_f is 0.1 and central frequency $\omega_c = 81$.

4.2 Results

4.2.1 High friction-flat load test

First, the vehicle test was conducted at high friction on flat load, and the results are shown in Fig. 4. In case of no control, wheel slip occurs during acceleration. Also, huge vibration is generated on wheel speed which causes noise and jolt feeling. On the other hand, the conventional DOB-based control algorithm shows good traction performance compared to the case without control. In case of the proposed control algorithm, it has superior traction performance as well as good riding comfort better than the conventional DOB-based control algorithm.

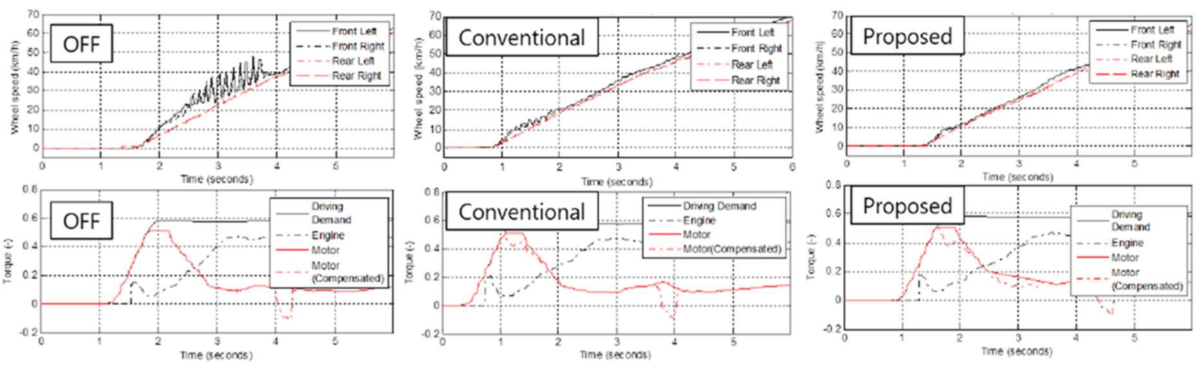

Figure 4. Test results of high friction-flat load

4.2.2 Low friction-flat load test

Next, the vehicle test was conducted at low friction on flat load, and the results are shown in Fig. 5. When the control is not applied, a very large wheel slip occurs; it also generates significant vibrations, causing noise and shock. According to the results using a conventional DOB, the amount of wheel slip is reduced compared to the case without control because the DOB estimates the wheel slip caused by the change in road friction as model error. However, there still exists vibrations of wheel speed that cause noise and jolt feeling. The disturbance of the low friction road is quite large thus wheel slip still occurs even if the drive torque is compensated. As shown in the result, the amount of the wheel slip with the proposed controller is reduced than with the conventional DOB. Therefore, the proposed control algorithm has better traction control performance and provides better ride comfort than conventional DOB control algorithm.

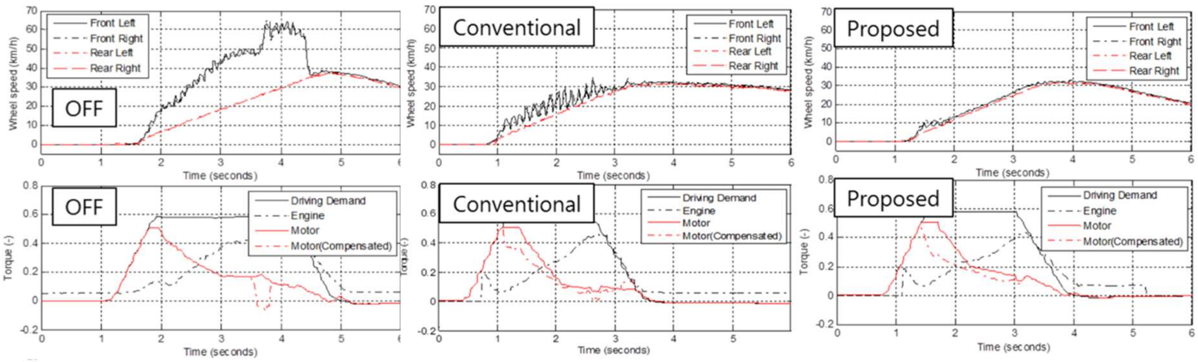

Figure 5. Test results of low friction-flat load

4.2.3 Uphill test

Last, in order to validate the anti wheel slip performance of the proposed control algorithm regarding weight shifting effect of the vehicle, vehicle test has been conducted on 20% slop road, and the results are shown in Fig. 6. On the uphill load, the traction force of the front wheels is lost because the weight of the vehicle is shifted to the rear. In case of no control, large wheel slip occurs. And huge vibration and noise are generated. The conventional DOB shows some good performance in reducing wheel slip, but more amount of wheel slip occurs in the initial launch range compared to the high friction-flat load test. Also, some amount of wheel slip still exists even after the vehicle speed increases because the steady state error is not eliminated. However, the proposed controller does not have this problem and has excellent performance than the conventional controller.

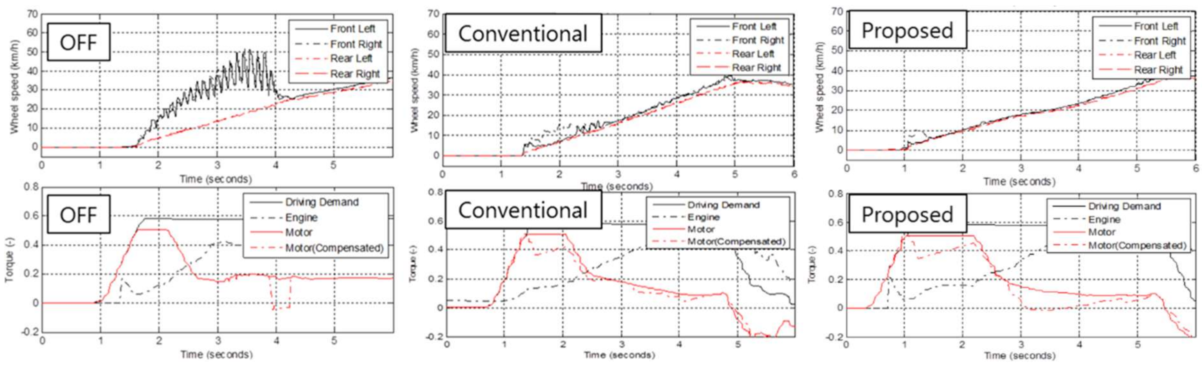

Figure 6. Test results of uphill

5 Conclusion

In this paper, a modified DOB-structured traction control algorithm is proposed. The proposed control technique is designed using the DOB to lump both model uncertainty and other disturbances as one disturbance. In addition, the BPF is used to extract disturbances at relatively high frequencies and minimize noise, allowing only the disturbances generated by wheel slip to be estimated. Moreover, PI compensator is applied to reduce the disturbance effectively. In order to verify the validity of the proposed control algorithm, a vehicle test is performed compared with the conventional DOB control technique. As a result, the proposed controller achieves superior anti wheel slip performance compared to the conventional controller. The amount of wheel slip is reduced under overall test conditions. The proposed controller can be an effective solution for the development of an electrified powertrain systems as for mass productions, since it is simple to implement as well as robust in disturbance.

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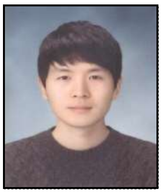
Presenter Biography



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