Study on Cornering Stability Control Based on Pneumatic Trail Estimation by Using Dual Pitman Arm Type Steer-By-Wire on Electric Vehicle

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***Abstract*—This paper proposes novel high accuracy road condition estimation called Tire Grip Margin (TGM), and TGM is estimated by using dual pitman arm type steer-by-wire and lateral force sensor and estimator. In addition, we propose cornering stability control technique based on the TGM. It can help driver and vehicle before unstable state. We verify our proposed system achieves robust vehicle dynamics control on the low friction road by CarSim. CarSim is simulator for the vehicle dynamics.**

Keywords-active front steering; electric power steering; electric vehicle; in-wheel motor; pitman arm; pneumatic trail; steer-by-wire; tire grip margin;

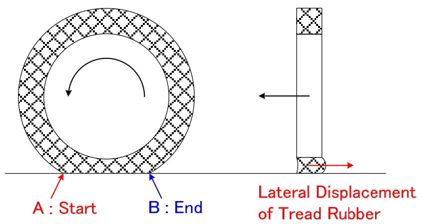
I. Introduction

In recent years, the demand for safer vehicles has increased. According to traffic accident reports prepared by Institute for Traffic Accident Research and Data Analysis (ITARDA) in Japan, almost all traffic accidents are caused by human errors such as driver negligence or operational mistakes. Therefore, future technologies need to precisely detect driver's mistakes and adopt active control in order to increase vehicle safety. In the recent decade, reserch and development of automotive company and university have proposed vehicle dynamics control techniques equipped with advanced active control capability such as Intelligent Tutoring System (ITS) and everything else and verified the experimental efficacy. However, almost all of them are inefficient on the low friction road and split-μ road had different friction on the right road and left road. In comparison, our proposed control technique will provide robust vehicle dynamics under any road friction circumstance. There is a general knowledge that controlling the yaw rate on vehicle is stabilizing vehicle dynamics. However, it is a half of mistake. Because controlling friction between tire and road surface is most important and fundamental to control stable yaw rate. Before now, there are some technical paper about tire friction control such as tire friction circle estimation [1] and slip μ estimation. However, they have enormous calculation amount and model error because of using very complicated model. In this paper, our proposed method estimate pneumatic trail with a very simple model. And we show that it is effective to estimate tire friction limit (tire grip margin). In addition, we propose a novel cornering stability control technique based on the tire grip margin with active front steering and in-wheel motor on electric vehicle. Finally, we verify the technique by the vehicle dynamics simulator CarSim.

II. Tire Grip Margin (TGM)

A. Ground Contact Length of Tire and Lateral Displacement of Tire Tread Rubber

A Tire has ground contact length caused by vehicle load, deflection because tire is made of hollow rubber. It is about 15-20 [cm]. When a tire is rolled ground contact is started. After a few second, it is ended. The ground contact length is between start position and end position. It is shown in Fig.1 (a).



(a) Ground contact (b) Lateral displacement

Fig. 1. Lateral displacement of tire ground contact.

On the other hand, when a tire is slid to lateral direction shown in Fig.1 (b) tread rubber of tire is displaced toward lateral position against wheel assumed rigid body. In this regard, the lateral displacement is not a uniform state in the ground contact of tire. The ground contact added tire slip angle α from above is shown in Fig.2. The center line x is direction of the tire before turning a steering wheel. After turning it, the tire is slid to the lateral direction by the slip angle α. The point A is starting ground contact. The point B is finishing it. From point A to point C, the tire tread rubber is dragged by road friction along with line α and is an adhesion state. From point C to point A, the tread between tire and road is slip state. The lateral force of tire equation is shown in (1).

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$$F_y = K_s \int_A^B y \, dx \tag{1}$$

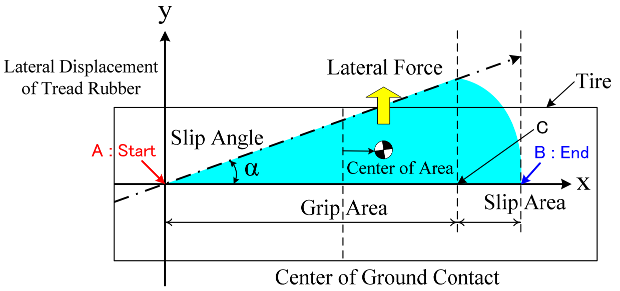

Fig. 2. Lateral displacement added slip angle.

Firstly, the force is given by multiplying the lateral stiffness K_s of the tread rubber by the area of the lateral deflection integrated form A to B. To the next, it is necessary to consider the center of the lateral force area. That is to say, it is a center position of the triangle area. The position is expected to be behind center of the tire ground contact. The distance between the center of the lateral force area and the center of the tire ground contact is known as pneumatic trail.

B. Tire Grip Margin (TGM) Difinition

A pneumatic trail as a moment arm, a lateral force and a self aligning torque are shown in the Fig. 3 and the following equation (2). When the pneumatic trail become zero or minus value, the tire experience slip phenomenon. We define the state variation of the pneumatic trail as the tire grip margin Δt.

$$\Delta t = T_{SAT} / F_y \tag{2}$$

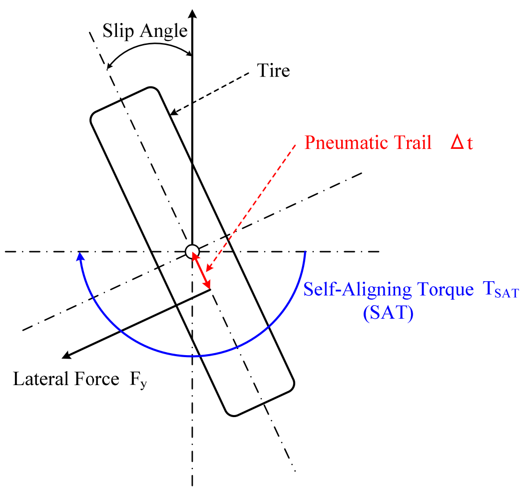

Fig. 3. Lateral force and self aligning torque.

C. Tire Grip Margin (TGM) Estimation

SAT and the lateral force need to be measured or estimated to calculate TGM. First, the lateral force can be measured using the tire hub sensor produced by NSK in Japan. The technical paper [2] proposes to estimate it using a resolver signal. About SAT, Our technical papers [3], [4] propose to estimate it using the road reaction torque observer with an electric power steering. The observer is shown in Fig. 6. In this regard, the time constant value needs to be large to estimate SAT with Q filter design.

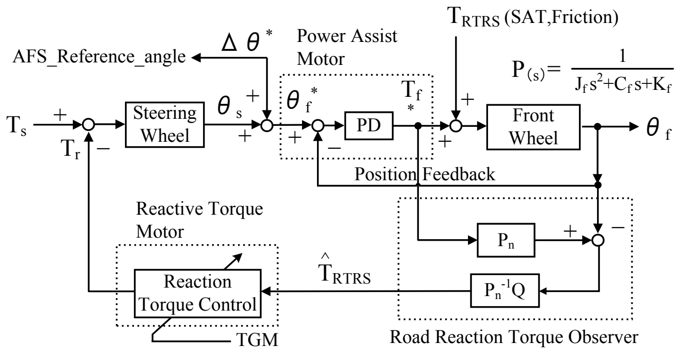

Fig. 4. Road reaction torque observer.

The electric power steering is shown in Fig. 5. This motor attached to the steering wheel axle is used for reactive torque control for a driver. The system uses other two motors to control the front tires independently. In addition, it estimates TGMs with these motors and the observer. The system can control optimal vehicle dynamics estimating four TGMs. It has potential advantage to stabilize vehicle motion under any road condition.

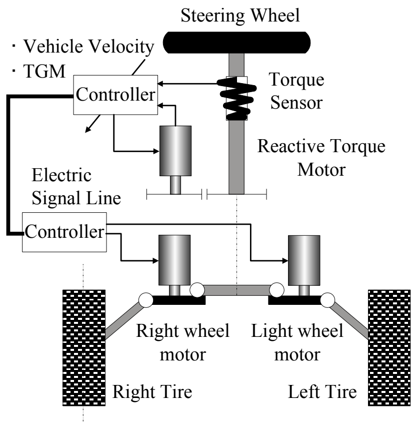

Fig. 5. Dual Pitman arm type steer-by-wire.

D. Road Reaction Torque Observer (RTOB)

As mentioned above, the reactive torque must be measured or estimated to transmit this information to the driver. In this study, we estimated the torque using an assist motor attached to the front axle wheel and an observer.

The block diagram of the reactive torque observer is shown in Fig. 4. The reaction torque T_{RTRS} from the road surface is an unknown state variable to be estimated. First, the estimated angle of the front axle wheel, $\hat{\theta}_f$, is calculated using the nominal model $P_n(s)$ of plant $P(s)$ and the reference torque of the front axle wheel, T_f^*, which are known state variables. Second, $\Delta\theta$ is calculated as the difference between the estimated value $\hat{\theta}_f$ and the measured value θ_f . $\hat{T}_{RTRS}$ is calculated by means of the inverse model P_n^{-1} of the plant. Since P_n^{-1} is not a proper function, $\hat{T}_{RTRS}$ is calculated using a low-pass filter Q . The formula is shown below.

$$\theta_f = \left(T_f^* + T_{RTRS}\right)P(s) \; , \; \hat{\theta}_f = T_f^* \cdot P(s) \tag{3}$$

$$\hat{T}_{RTRS} = \left(\theta_f - \hat{\theta}_f\right)P_n^{-1}(s) \cdot Q(s) \tag{4}$$

If the nominal model $P_n(s)$ is confirmed to be identical to plant $P(s)$, $\hat{T}_{RTRS}$ is calculated by the following formula.

$$\hat{T}_{RTRS} = T_{RTRS} \cdot Q(s) \tag{5}$$

$P(s)$ is identified using the Prediction Error Method based on the Maximum-Likelihood Method.

Low pass filter Q reduces higher frequency gain than cut-off frequency $1/\tau_q$. τ_q is time constant value. If the reaction torque $\hat{T}_{RTRS}$ estimated by the observer were to be directly transmitted to the driver, the control would cause steering interference in the same manner as the differential angle control, as shown in Fig. 8. Therefore, it is necessary to adjust the gain and frequency of $\hat{T}_{RTRS}$ with the low-pass filter Q . In this regard, the time constant value needs to be large to estimate SAT with Q filter design.

$$Q(s) = \frac{1}{1 + 2\tau_q s + \tau_q^2 s^2} \tag{6}$$

III. VEHICLE DYNAMICS CONTROL

Driver controls a vehicle dynamics with operating a front axle wheel angle via a steering wheel. This paper shows the following vehicle dynamics equation. The vehicle state equation on two-dimensional model shown in Fig.6 describes vehicle velocity V around center of gravity, chassis slip angle β and yaw rate γ. Vehicle mass M [kg], vehicle inertia I_z [kgm], distance between center of gravity and front tire l_f [m], distance between center of gravity and rear tire l_r [m], front cornering stiffness K_f [N/rad], rear cornering stiffness K_r [N/rad]. And lateral motion of a tire is shown in Fig. 3. If a driver turns front axle wheel angle via steering wheel, lateral force F_y proportional to tire slip angle α is generated between tire and road surface. The lateral force varies considerably depending on road condition like Fig.7. In case of dry road, it is linear characteristics from 0 to 10 [deg]. However, that of more than 10 [deg] is nonlinear characteristics.

1) Lateral Force

$$F_f = F_{fL} = F_{fR} = -K_f * \left(\frac{V * \beta + l_r * \gamma}{V} - \delta_f\right) \tag{7}$$

$$F_r = F_{rL} = F_{rR} = -K_r * \left(\frac{V * \beta - l_f * \gamma}{V}\right) \tag{8}$$

2) Lateral Motion Equation

$$M_z * V * \left(\frac{d\beta}{dt} + \gamma\right) = (F_{fL} + F_{fR}) + (F_{rL} + F_{rR}) \tag{9}$$

$$= 2 * F_f - 2 * F_r \tag{10}$$

The lateral forces F_f and F_r generate yaw moment γ around center of gravity on a vehicle.

3) Rotational Motion Equation

$$I_z * \frac{d\gamma}{dt} = l_r * (F_{fL} + F_{fR}) - l_f * (F_{rL} + F_{rR}) + M \tag{11}$$

$$= 2 * l_r * F_f - 2 * l_f * F_r + M \tag{12}$$

M is yaw moment by differential torque. In this study, the torque is directly generated with two In-wheel motors on electric vehicle.

4) State Equation for Vehicle Dynamics

$$\dot{x} = Ax + BM + H\delta_f \quad , \quad x = [\beta \quad \gamma]^t \tag{13}$$

$$A = \begin{bmatrix} -2\dfrac{K_f + K_r}{M_z V} & -1 - 2\dfrac{l_f K_f - l_r K_r}{M_z V^2} \\ -2\dfrac{l_f K_f - l_r K_r}{I_z} & -2\dfrac{l_f^2 K_f - l_r^2 K_r}{I_z V} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & \dfrac{1}{I_z} \end{bmatrix}^t \quad , \quad H = \begin{bmatrix} \dfrac{2K_f}{M_z V} & \dfrac{2 l_f K_f}{I_z} \end{bmatrix}^t \tag{14}$$

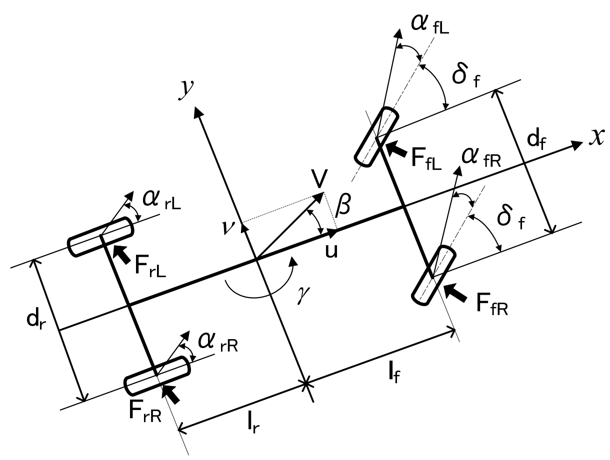

Fig. 6. Vehicle Model.

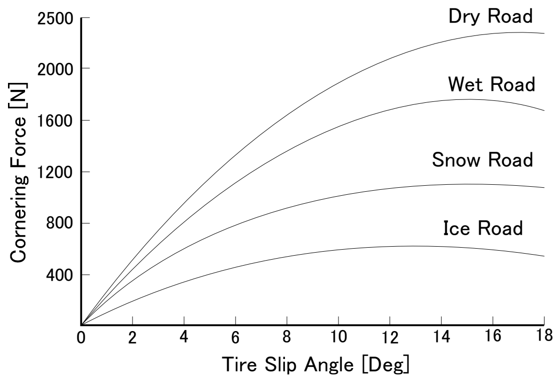

Fig. 7. Lateral force vs. road condition.

A. Steering Control Technique

When TGM of the front tire is smaller than 5 [mm], the steering system increases reactive torque for a driver. It helps driver turn the steering wheel to reduce the sideslip of the tire. In addition, the driver can recognize road information and tire grip state via reactive torque. The reactive torque equation is shown in (15).

$$T_r = K_t \hat{T}_{RTRS} \tag{15}$$

$$\{\text{If } \Delta t > 5\ ,\ K_t = K_{a0}\ \text{(constant value)}\}$$

$$\{\text{If } \Delta t \le 5\ ,\ K_t = \frac{K_{a0}}{\Delta t}\ \}$$

B. In-wheel Motor Control

The experimental device has two In-wheel motors in rear wheels. When TGM of the front tire is smaller than 5 [mm], the motor controller reduced the reference torque. The system always maintains the rear tires to be grip state. In addition, the yaw moment on the vehicle is controlled by using the differential torque M with In-wheel motor. Right wheel traction torque is F_{Rd} and left one is F_{Ld}. The differential torque M is shown in (16). The moment compensates the front lateral force reduced by TGM steering control.

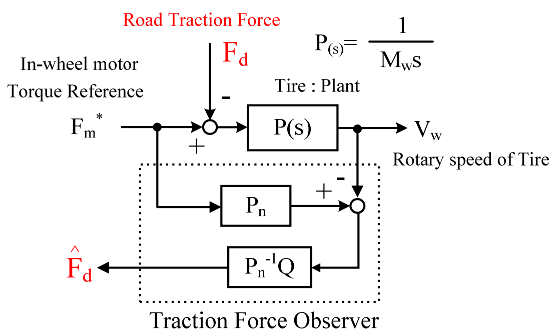

Fig. 8. Torque control for in-wheel motor.

$$M = \frac{d_r}{2}\left(F_{Ld} - F_{Rd}\right) \tag{16}$$

IV. EXPERIMENTAL METHOD

A. Experimental Vehicle

This paper adopts COMS produced by Toyota Auto Body as experimental vehicle. COMS is a compact electric vehicle equipped with two in-wheel motors operated independently in the right and left wheels. (Fig. 9) the steering system is dual pitman arm type steer-by-wire.

Fig. 9. Electric vehicle COMS

Fig. 10. In-wheel motor (Direct drive motor).

Fig. 11. Driver-friendly reactive torque motor.

B. Driving Condition

The experiment simulates dabble lane change. Then, the vehicle velocity is 100 [km/h], road condition is snow and road friction coefficient μ is 0.5. The driver model is preview driver type.

V. EXPERIMENTAL VERIFICATION

The experimental results are shown in Fig. 12. In Fig.12 (a), without TGM control could not trace the reference driving lane. In the result, it slides off the track. On the other hand, with TGM control could achieve trace it. About yaw rate in Fig.12 (b), TGM control stabilizes the yaw rate. Each tires grip margin are shown in Fig.12 (c)-(f). When TGM control is disabled, the grip margin is smaller than zero, it shows that the tire is in slip phenomenon. That is to say, the proposed system controls TGMs of each tire not to be smaller than zero by using the steering wheel angle and in-wheel motor torque. In fig. 12 (g), when TGM of the front tires is smaller than 5 [mm] it controls to help the driver return the steering wheel angle. When TGM of the rear tires is smaller than 5 [mm] it reduces the traction torque, avoids the slip.

VI. CONCLUSION

This paper shows the Tire Grip Margin (TGM) with the road reaction observer and the lateral force sensor is effective technique to estimate the high accuracy road condition. In addition, we propose cornering stability technique based on the TGM in vehicle. It can help driver and vehicle before unstable state. This paper verifies our proposed system achieves robust cornering stability control on the low friction road with vehicle dynamics simulator CarSim. In the future works, we verify optimum cornering stability control based on TGM.

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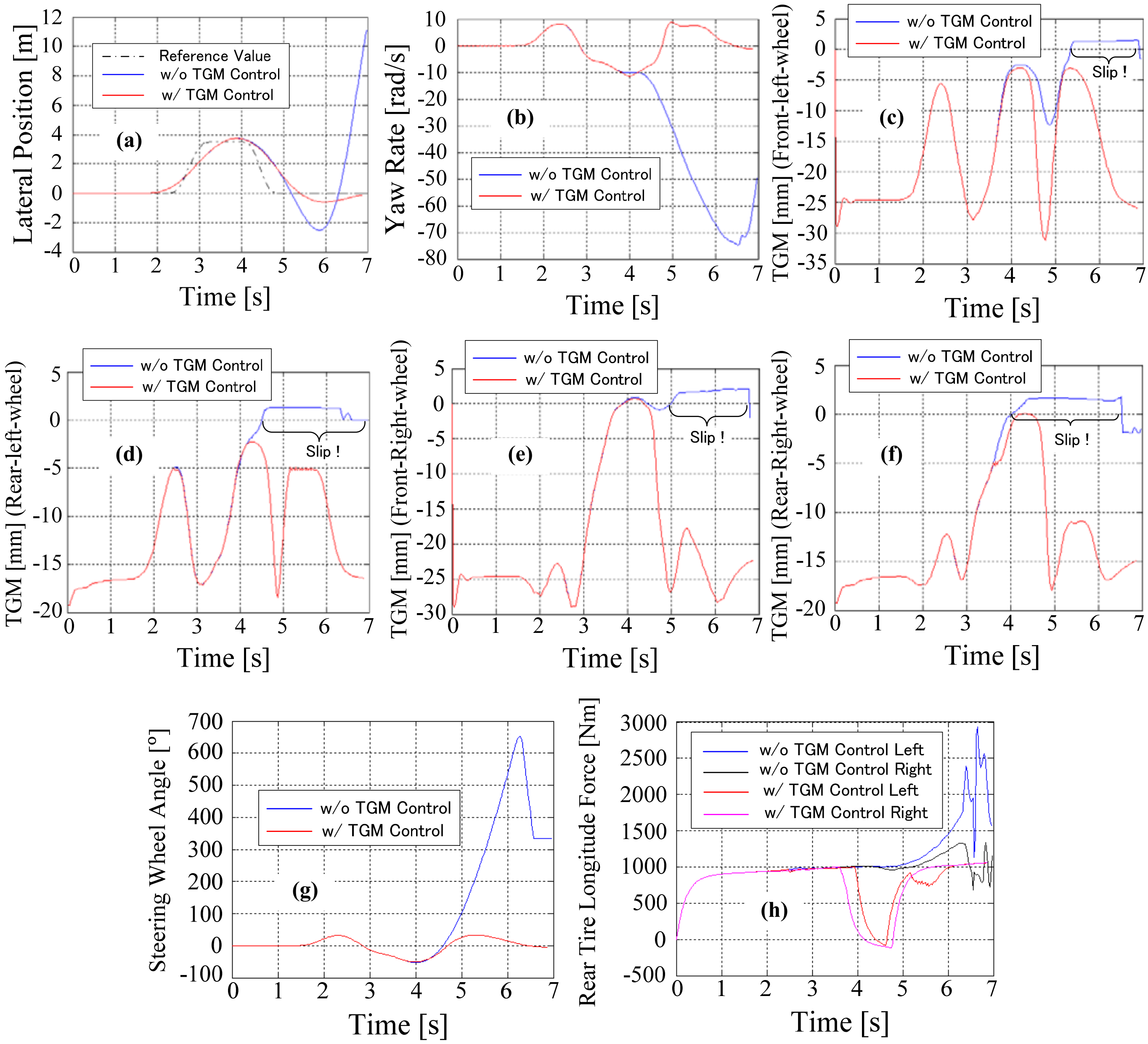

Fig. 12. Experimental result.