Rolling Stability Control Based on Electronic Stability Program for In-wheel-motor Electric Vehicle

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***Abstract*—In this paper, a novel robust roll stability control (RSC) based on electronic stability program for electric vehicle (EV) is proposed. Since EVs are driven by electric motors, they have the following four remarkable advantages: (1) motor torque generation is quick and accurate; (2) motor torque can be estimated precisely; (3) a motor can be attached to each wheel; and (4) motor can output negative torque as a brake actuator. These advantages enable high performance vehicle motion control. Furthermore, 3-dimensional motion controls are realized with a distributed in-wheel-motor system. RSC utilizing two-degree-of-freedom control is proposed and the validity of the proposed control is demonstrated by both simulation and experimental results.**

***Index Terms*—rolling stability control, electric stability program, electric vehicle, disturbance observer, two-degrees-of-freedom control, identification**

I. INTRODUCTION

A. In-wheel-Motor Electric Vehicle's Advantages and Application for Vehicle Motion Control

In-wheel-motor EV can realize high performance motion control utilizing advantages of electric motors which internal combustion engines do not have. Electric vehicle (EV) has the following four remarkable advantages [1]:

- Motor torque response is 10-100 times faster than that of internal combustion engine's one. This enables to realize high performance adhesion control, skid prevention and slip control.
- Motor torque can be measured easily by observing motor current. This property can be used for road condition estimation.
- Since an electric motor is compact and inexpensive, it can be equipped for each wheel. This feature realizes three dimensional high performance vehicle motion control.
- There is no difference between acceleration and deceleration control. This actuator advantage enables high performance braking control.

Slip prevention control is proposed utilizing fast torque response [1]. Road condition and skid detection methods are developed utilizing the advantage that torque can be measured easily [1]. Yaw control, side slip angle estimation and control methods are also proposed with a distributed in-wheel-motor system [2] - [4].

B. Background and Target of the Research

According to the data from NHTSA, ratio of rollover accidents of pick ups' and vans' crashes in 2002 was only 3% against whole accidents. However, fatalities due to rollover accidents are nearly 33% of all deaths from passenger vehicle crashes[5]. Therefore, rolling stability control (RSC) is very important not only for ride quality but also for safety, especially on pick ups and vans. The RSC system has been developed by several automotive makers and universities [6] [7]. Rollover detection systems, such as Roll-index (RI) [8] and Time-to-rollover (TTR) [9] are proposed for mitigating critical rolling motion.

Every system controls braking force on each wheel independently and suppresses sudden increase of lateral acceleration or roll rate. However, since braking force is the average value achieved by pulse width modulation control of brake pad, brake system cannot output precise torque nor positive torque. In the case of in-wheel-motor, both traction and braking force controls can be realized quickly and precisely.

In this paper, RSC is designed utilizing two-degrees-of-freedom (2-DOF) control based on disturbance observer (DOB) [10]. DOB is applied to several automotive researches. In the vehicle motion control field, DOB is applied to vehicle yaw/pitch rate control [2] [3] and 2-DOF control is applied to the electric power steering control [11]. The following capability and robustness for lateral acceleration disturbance such as side blast or road bank, are realized by the proposed method.

C. Electronic Stability Program for Electric Vehicle

Fig. 1 shows concept of electronic stability program (ESP) for EV. ESP consists of two parts; Vehicle/Road state estimation system (S1) and Vehicle dynamics control system (S2). S1 integrates information from sensors (accelerometer, gyro, GPS, suspension stroke, steering angle sensors) and estimate unknown vehicle parameters (mass, body slip angle, roll/pitch angle and longitudinal/lateral forces on tires) [7] [12].

According to the information from S1, S2 controls vehicle dynamics using yawing/rolling stability control (YSC/RSC), pitching stability control (PSC) and anti-slip control (ASC). According to RI, which is calculated by S1, a proper stability control strategy (YSC, RSC or mixed) is determined. RI is expressed as following equation,

$$
\begin{aligned}
RI &= C_1\Big(\frac{|\phi|\dot{\phi}_{th}+|\dot{\phi}|\phi_{th}}{\phi_{th}\dot{\phi}_{th}})+C_2(\frac{|a_y|}{a_{yc}},\\
&\quad +(1-C_1-C_2)(\frac{|\phi|}{\sqrt{\phi^2+\dot{\phi}^2}})\Big),\ \text{if}\ \phi(\dot{\phi}-k_1\phi)>0,\\
RI &= 0,\quad \text{else if}\quad \phi(\dot{\phi}-k_1\phi)\le 0. \qquad (1)
\end{aligned}
$$

where ϕ_{th}, $\dot{\phi}_{th}$ are roll angle and roll rate threshold, a_{yc} is critical lateral acceleration that may induce rollover, ϕ and $\dot{\phi}$ is roll angle and roll rate. C_1,C_2,k_1 are determined by actual vehicle model.

S2 is based on disturbance observer and nominal vehicle state is calculated by computer. If there exists error between calculated dynamics and actual ones, it is corrected by differential torque.

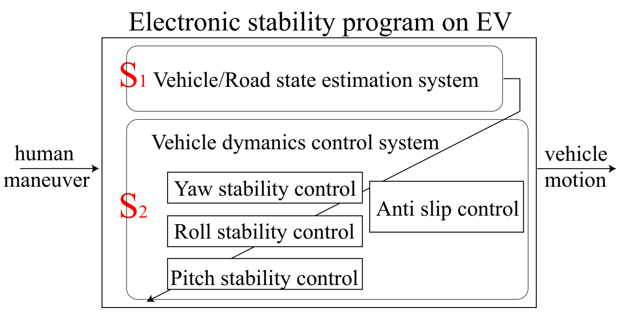


Fig. 1. Electronic stability program based on disturbance observer

II. Vehicle Model

The vehicle model used linear suspension roll model [13]. Model parameter identification is conducted using constant trace method.

A. Linear Suspension Roll Model

The roll motion equation is expressed by the following equation [13],

$$
\begin{aligned}
&-Mh_sVs\beta-I_{xz}s\gamma-Mh_sV\gamma\\
&+(I_{roll}s^2+C_{roll}s+K_{roll}-Mgh)\phi=0. \qquad (2)
\end{aligned}
$$

where s is Laplace operator, M is vehicle weight, h_s is distance between CG and roll center, V is vehicle speed, β is body slip angle, I_{xz} is product of inertia, γ is yaw rate, I_{roll}, C_{roll} and K_{roll} are inertia factors, damping factor and spring factor of roll motion respectively, g is gravity and h is height of CG.

Lateral acceleration on CG a_y, is represented by the following equation using body side slip angle, yaw rate and vehicle velocity.

$$a_y=(s\beta+\gamma)V \qquad (3)$$

Using eq. (3), the roll motion equation becomes,

$$
\begin{aligned}
Mh_sa_y &\quad +I_{xz}s\gamma\\
&= (I_{roll}s^2+C_{roll}s+K_{roll}-Mgh_s)\phi. \qquad (4)
\end{aligned}
$$

Since product of inertia is sufficiently small and gravity term is also very small, the roll motion equation is equivalent to a linear mass-spring-damper system:

$$\phi=\frac{Mh_s}{I_{roll}s^2+C_{roll}s+K_{roll}}a_y. \qquad (5)$$

To design disturbance obserber controller, roll model parameters are required. In the next section, the parameters are identified using extended least square method (constant trace method).

B. Model parameter identification

Constant trace method is applied to the rolling model parameters identification [14]. From equation (5), lateral acceleration $\hat{a_y}$ is written as

$$\hat{a_y}(k|\theta) \quad = \quad \hat{\theta}^T\zeta(k). \qquad (6)$$

Where $\theta=\begin{bmatrix} I_{roll} & C_{roll} & K_{roll}\end{bmatrix}^T$, $\zeta=\begin{bmatrix}\ddot{\phi} & \dot{\phi} & \phi\end{bmatrix}^T$.

The algorithm of the constant trace method is to update forgetting factor λ, such that trace of gain matrix P, is maintained as constant.

$$tr(P(k+1))=\frac{1}{\lambda(k)}tr(P(k)-\frac{P(k)\zeta(k)\zeta^T(k)P(k)}{1+\zeta^T(k)P(k)\zeta(k)}) \qquad (7)$$

Due to the forgetting factor, when ζ is big, θ can be identified with good precision, and when ζ is small and little information, θ is seldom updated. With constant trace method, stable parameter estimation is achieved.

Update equation is written by the following equation.

$$
\begin{aligned}
\epsilon(k) &= y(k)-\hat{\theta}^T(k-1)\zeta(k), \qquad (8)\\
\hat{\theta}(k) &= \hat{\theta}(k-1)+\frac{P(k-1)\zeta(k)}{1+\zeta^T(k)P(k-1)\zeta(k)}\epsilon(k), \qquad (9)\\
P(k) &= \frac{1}{\lambda}(P(k-1)\\
&\quad -\frac{P(k-1)\zeta(k)\zeta^T(k)P(k-1)}{1+\zeta^T(k)P(k-1)\zeta(k)}), \qquad (10)\\
\lambda(k) &= 1-\frac{|P(k-1)\zeta(k)|}{1+\zeta^T(k)P(k)\zeta(k)}\frac{1}{tr[P(0)]}. \qquad (11)
\end{aligned}
$$

Where ϵ is output error. Utilizing constant trace method to the experimental result, angular frequency $\sqrt{\frac{K_{roll}}{I_{roll}}}$ = 17.2 (rad/sec) and damping coefficient $\sqrt{\frac{1}{2I_{roll}K_{roll}}}C_{roll}$ = 0.234 (1/sec). Fig. 2 shows detected acceleration information by sensor and calculated acceleration with estimated parameter $\hat{\theta}$ and ζ. From the figure, the two lines merge and parameter identification is succeeded.

III. Roll Stability Control based on Two-Degrees-of-Freedom Control

A. Following Capability with Feedback Controller

Fig. 3 shows the block diagram of RSC based on basic feedforward (FF) and feedback (FB) control. Where δ is steering angle, V is vehicle speed, ϕ is roll angle, a_y is lateral acceleration and M is differential torque. Outside of the dashed line corresponds to the real system, while inside

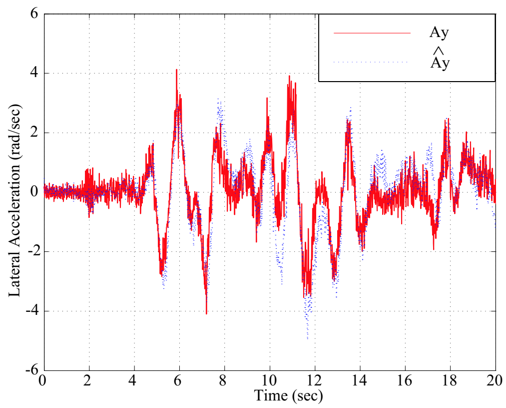


Fig. 2. Rolling model parameter identification

is the rolling stability controller. Roll moment is applied by differential torque M^* with right and left in-wheel-motors. Reference value of roll rate is given by steering angle and vehicle velocity. The FF controller compensates system delay

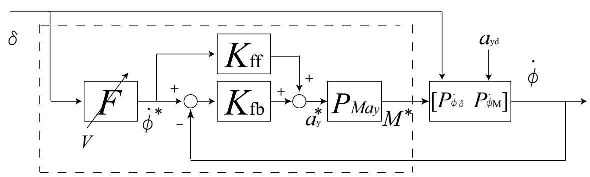


Fig. 3. Block diagram of roll stability control based on basic FF and FB controller

and improves stability of the system, where a_{yd} is disturbance lateral acceleration.

B. Robustness for Lateral Acceleration Disturbance

In general, a combination of FF and FB control is called two-degrees-of-freedom control. However, basic FF and FB controller cannot suppress disturbances. Hence two-degrees-of-freedom control in terms of following capability and disturbance suppression is proposed in this section. Proposed lateral acceleration DOB estimates external disturbance to the system using information, vehicle velocity, steering angle, differential torque and roll rate. Fig. 4 shows the block diagram of lateral acceleration DOB.

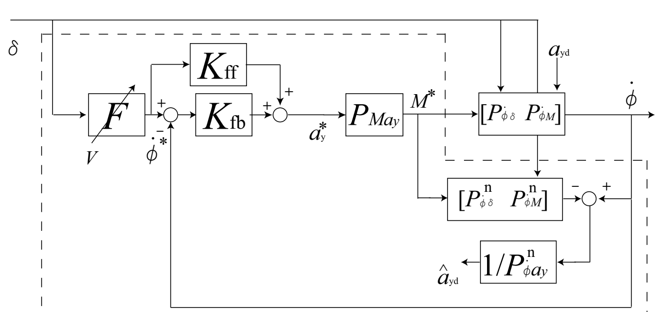


Fig. 4. Block diagram of lateral acceleration DOB

Estimated lateral acceleration disturbance $\hat{a}_{yd}$ and ϕ are

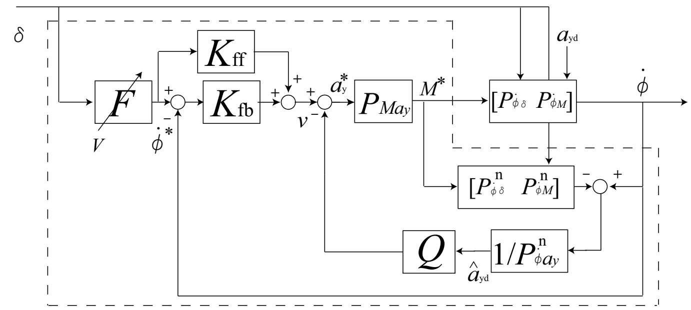


Fig. 5. Block diagram of 2-DOF for RSC based on DOB

expressed as

$$\hat{a}_{yd} = \frac{1}{P^n_{\dot{\phi}a_y}}(\dot{\phi} - P^n_{\dot{\phi}a_y}a_y^* - P^n_{\dot{\phi}\delta}\delta), \tag{12}$$

$$\dot{\phi} = P_{\dot{\phi}a_y}(P_{a_yM}M^* + P_{a_y\delta}\delta + a_{yd}). \tag{13}$$

Suppose, $P_{a_yM}M^* = a_y^*$ and delete a_y^* from eq. (12) and (13),

$$\hat{a}_{yd} = \left(\frac{1}{P^n_{\dot{\phi}a_y}} - \frac{1}{P_{\dot{\phi}a_y}}\right)\dot{\phi} - (P^n_{a_y\delta} - P_{a_y\delta})\delta + a_{yd} \tag{14}$$

In eq. (14), first and second terms are model errors and third term is lateral disturbance.

Fig. 5 shows the proposed 2-DOF control for RSC. The observer loop is inside the FF and FB controller. It means DOB response is relatively faster than outer loop. Estimated lateral acceleration disturbance is fedback to lateral acceleration input.

$$a_y^* = v - Q\hat{a}_{yd}. \tag{15}$$

Filter Q is low pass filter and expressed as following equation [15]. In this study, the cut off frequency is set as 20 (rad/sec).

$$Q = \frac{1 + \sum_{k=1}^{N-r} a_k(\tau s)^k}{1 + \sum_{k=1}^{N} a_k(\tau s)^k}. \tag{16}$$

Where r must be equal or greater than relative order of the transfer function of the nominal plant. Plug in eq. (15) to eq. (12),

$$\dot{\phi} = P^n_{\dot{\phi}\delta}\delta + P^n_{\dot{\phi}M}P^n_{Ma_y}v + P^n_{\dot{\phi}a_y}(1-Q)\hat{a}_{yd}. \tag{17}$$

If frequency of disturbance is lower than the cut off frequency of Q, DOB suppresses the external disturbance. In addition to the function of disturbance rejection, the plant is nearly equal to nominal model in lower frequency region than cut off frequency. Therefore the proposed RSC has the function of model following control.

IV. Simulation and Experimental Results

A. Following Capability of RSC

Experimental conditions are following;
-4.0m/s constant velocity drive
-1.8 (rad/sec) sinusoidal wave steering maneuver
-reference roll rate $\dot{\phi}^*$ is half of nominal roll rate

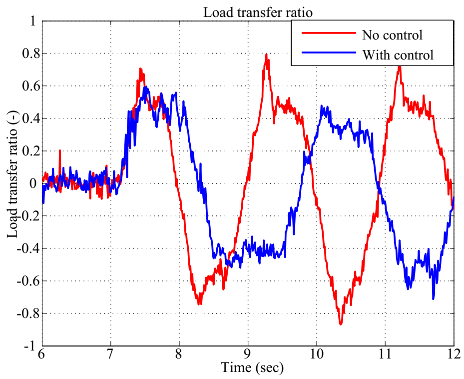


Fig. 6. Comparison of rolling performance factor LTR

Fig. 6 shows experimental result of LTR. LTR is RSC index and is defined as following equation.

$$\begin{aligned} LTR &= \frac{F_{zfl} - F_{zfr} + F_{zrl} - F_{zrr}}{F_{zfl} + F_{zfr} + F_{zrl} + F_{zrr}}, \\ |LTR| &\leq 1.0, \end{aligned} \quad (18)$$

Where F_{zxx} is normal force on each tire. When the proposed control is activated, peak of LTR is suppressed by differential torque. Even though perfect tracking is impossible due to the torque limitation of in-wheel-motor system and roll dynamics, roll rate by sinusoidal steering input is effectively suppressed.

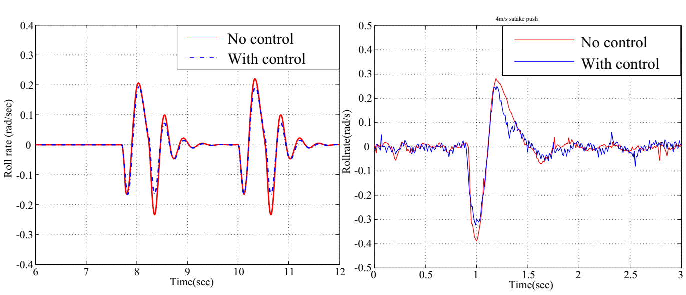
B. Disturbance Suppression of RSC

Experimental conditions are following.

-4.0m/s constant velocity straight drive

-One-period sinusoidal lateral disturbance input

Fig. 7 (a) and (b) show the robustness of the proposed method. It is assumed that lateral blast, which is realized by 6 (rad/sec) sinusoidal wave, is input to the vehicle at 7.7 (sec). When the control strategy is activated, the proposed lateral acceleration DOB detects and suppresses the lateral disturbance. Compared to the case of no control, the differential torque of right and left motors suppresses peak of roll rate. The robustness of proposed 2-DOF control is verified by experimental results.



(a) Simulation result　　(b) Experimental result

Fig. 7. Simulation result of disturbance suppression

V. Conclusion and Future Works

In this paper, a novel RSC utilizing electric motor's advantages based on ESP for in-wheel-motor EV is proposed . The validity of the proposed control is demonstrated by both simulation and experimental results in the third section.

In the present studies, only roll rate information is used for RSC. As the lateral acceleration information is not taken into account the disturbance rejection is not sufficient. As future work, RSC utilizes lateral acceleration information will be proposed.

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References

[1] Yoichi Hori, "Future Vehicle driven by Electricity and Control-Research on Four Wheel Motored UOT Electric March II", IEEE Transaction on Industrial Electronics, Vol.51, No.5, pp.954-962, 2004.10

[2] Hiroshi Fujimoto, Akio Tsumasaka, Toshihiko Noguchi, "Vehicle Stability Control of Small Electric Vehicle on Snowy Road", JSAE Review of Automotive Engineers, Vol. 27, No. 2, pp. 279-286, 2006.04

[3] Shinsuke Satou, Hiroshi Fujimoto, "Proposal of Pitching Control for Electric Vehicle with In-Wheel Motor", IIC-07-81 IEE Japan, pp.65-70, 2007.03 (in Japanese).

[4] Peng He, Yoichi Hori, "Improvement of EV Maneuverability and Safety by Dynamic Force Distribution with Disturbance Observer", WEVA-Journal, Vol.1, pp.258-263, 2007.05

[5] National highway traffic safety administration, Safercar program, http://www.nhtsa.gov/

[6] E. K. Liebemann, "Safety and Performance Enhancement: The Bosch Electronic Stability Control(ESP)", SAE Technical Paper Series, 2004-21-0060, 2004.10

[7] Hongtei E. Tseng, et al, "Estimation of land vehicle roll and pitch angles", Vehicle System Dynamics, Vol.45, No.5, pp.433-443, 2007.05

[8] Kyongsu Yi, et al, " Unified Chassis Control for Rollover Prevention, Maneuverability and Lateral Stability", AVEC2008, pp.708-713, 2008.10

[9] Bo-Chiuan Chen, Huei Peng,"Differential-Braking-Based Rollover Prevention for Sport Utility Vehicles with Human-in-the-loop Evaluations", Vehicle System Dynamics, Vol.36, No.4-5, pp359-389, 2001.

[10] Kiyotaka Kawashima, Toshiyuki Uchida, Yoichi Hori, "Rolling Stability Control of In-wheel Electric Vehicle Based on Two-Degree-of-Freedom Control", The 10th International Workshop on Advanced Motion Control, pp. 751-756, Trento Italy, 2008.03

[11] Bilin Aksun Guvenc, Tilman Bunte, Dirk Odenthal and Levent Guvenc, "Robust Two Degree-of-Freedom Vehicle Steering Controller Design", IEEE Transaction on Control Systems Technology, Vol. 12, No. 4, pp.627-636, 2004.07

[12] A. Hac, et. al, "Detection of Vehicle Rollover", SAE Technical Paper Series, 2004-01-1757, SAE World Congress, 2004.

[13] Masato Abe, "Vehicle dynamics and control", Sankaido, 2003.03 (in Japanese)

[14] Ioan D. Landau, Gianluca Zito, "Digital Control Systems", pp. 201-224, Springer, 2006

[15] Takaji Umeno, Yoichi Hori, "Robust Speed Control of DC Servomotors Using Modern Two Degrees-of-Freedom Controller Design", IEEE Transaction Industrial Electronics, Vol.38, No. 5, pp.363-368, 1991.10