Rolling Stability Control of In-wheel Electric Vehicle Based on Two-Degree of Freedom Control

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Abstract— **In this paper, a novel rolling stability control (RSC) on in-wheel electric vehicle based on two-degree of freedom control is proposed. Electric motors have several advantages which internal combustion engines or brake actuators do not have. Differential torque by right and left motors can realize novel vehicle motion controls. Although RSC systems have been developed by automobile and several parts companies, the actuators are only brake actuator systems and cannot output positive torque quickly and precisely. Electric motors can output accurate torque in both directions very quickly. In addition to the actuator advantage, two-degree of freedom control is applied for RSC. The proposed method realizes following capability to command value and robustness to roll moment disturbance. Roll model identified with experimental result is shown in the third section. Effectiveness of proposed roll stability control is verified with simulation and experimental results utilizing our two in-wheel electric motor on pure electric vehicle. With proposed RSC, peaks of roll rate and roll angle are suppressed for disturbance roll moment comparison to without control.**

I. INTRODUCTION

A. Current Situation of Electric Vehicle

Global warming is a very serious problem all over the world. World climate has changed significantly due to increase of CO_2. One quarter of CO_2 emission is related to automotive industries and environmental pollution in urban areas. Because pure electric vehicles (PEV) equip motors and batteries and are driven by electricity, CO_2 emission is lower than internal combustion engine vehicles. Mitsubishi Motors and Keio University announced they have developed in-wheel PEVs respectively. Keio Univ.'s PEV named ”ELIICA” [1] has 8 in-wheel motors and its acceleration comparable to modern sports cars'. Although PEVs have high drive performance due to small and efficient inverter and actuator, the battery has always been the bottle neck. The current battery is very heavy and its energy density is one order smaller than that of liquid fuel.

The problem is how we can spread the use of PEV in the future. By changing the point of view from environmental aspects on PEV we can focus on the motor's advantages which internal combustion engines or brake actuators do not have. With these advantages, in-wheel PEV can realize high performance vehicle motion control.

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

As we have pointed out, electric vehicle has the following four remarkable advantages [2] [3]:

- Motor torque response is 10-100 times faster than that of internal combustion engine. This advantage enables us 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 high performance vehicle motion control.
- There is no difference between acceleration and deceleration control. Just by changing the direction of motor current, the vehicle can be decelerated.

In-wheel PEV can realize high performance motion control utilizing advantages of electric motors which internal combustion engines do not have.

Slip prevention control is proposed by Hori and Sakai utilizing fast torque response [2] [3]. Road condition and skid detection methods are developed by Fujimoto and Sakai utilizing the advantage that torque can be known easily [3] [4]. Yaw control, beta estimation and control methods are also proposed by Aoki and He with a distributed in-wheel motor system [5] [6] [7] [8].

C. Background and Target of the Research

Rolling stability control (RSC) is very important not only for safety but also for ride quality. Instability of the normal force on each tire causes tire slip or poor ride quality. The RSC system has been developed by an automotive and several parts companies [9] [10] [11]. Each system controls braking force on each wheel independently and suppresses sudden increase of lateral acceleration or roll rate. However, braking force is average value made by pulse width modulation control of brake pad and cannot output precise torque. In the case of in-wheel motor, both traction and braking force can be realized quickly and precisely itself.

The proposed control method is based on two-degree of freedom (2-DOF) control. The following capability and robustness for roll moment disturbance, such as side blast or road bank, are realized by the proposed method. As 2-DOF controller can also change plant roll model to nominal roll model, the proposed RSC has the function of an adjustment function of the suspension system.

II. VEHICLE MODEL

The vehicle model used in this research consists of two models; a Magic formula based nonlinear four wheel vehicle model and a linear suspension roll model.

A. Four wheel model

1) Nonlinear tire model: Fig. 1 shows four wheel model.

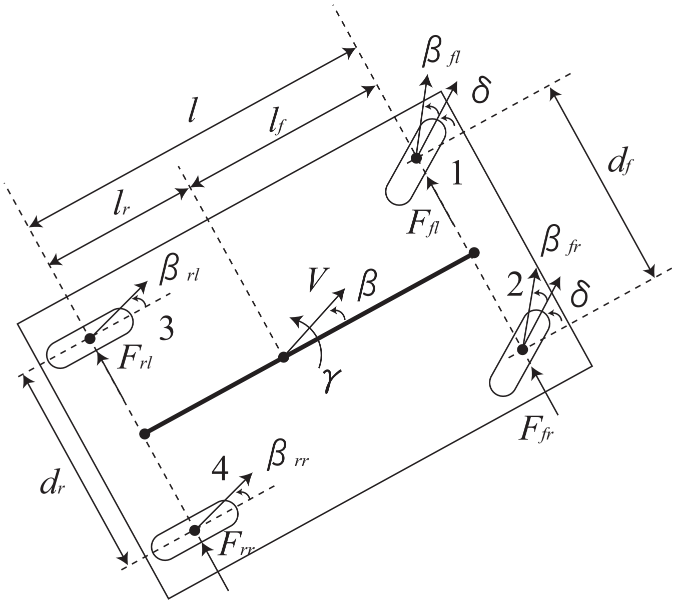


Fig. 1. Four wheel vehicle model

Lateral acceleration is caused by lateral forces on the four wheels. Lateral acceleration is derived by the Magic formula tire model using the body side slip angle β. Slide slip angle on each wheel is expressed by the following equations [12].

$$\beta_{fl} = \frac{V\beta + l_f r}{V - d_f \frac{r}{2}} - \delta, \tag{1}$$

$$\beta_{fr} = \frac{V\beta + l_f r}{V + d_f \frac{r}{2}} - \delta, \tag{2}$$

$$\beta_{rl} = \frac{V\beta - l_r r}{V - d_r \frac{r}{2}}, \tag{3}$$

$$\beta_{rr} = \frac{V\beta - l_r r}{V + d_r \frac{r}{2}}. \tag{4}$$

Where V is vehicle speed, γ is yaw rate, δ is steering angle, l_f, l_r are distances from center of gravity (CG) to the front and rear shafts, and d_f, d_r are distances between the front wheels and the rear wheels.

Lateral force F_y is expressed as using the Magic formula function $f(\beta)$

$$F_y = \sum_{i=1}^{4} F_i = \sum_{i=1}^{4} F(\beta_i). \tag{5}$$

The Magic formula function $f(\beta)$ is expressed by the following equation [13] [14],

$$f(x) = Dsin(Carctan(Bx - E(Bx - arctan(Bx)))) \tag{6}$$

Fig. 2 illustrates a typical side force characteristic. From the figure, the right side of peak can be realized as linear relation, and it is called the linear tire model. In this paper, we assume nonlinear tire model as expressed in eq. 6.

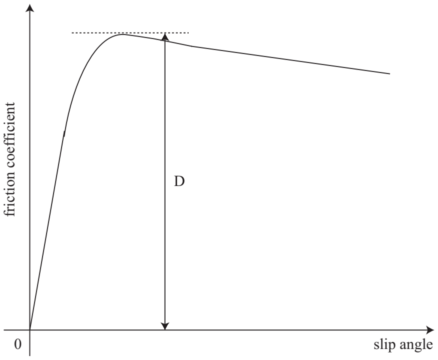


Fig. 2. Magic formula nonlinear tire model

2) Motion equation of four wheel vehicle: The lateral motion equation and rotational equation are expressed as

$$MV(s\beta + r) = -\sum_{i=1}^{4} F(\beta_i) \tag{7}$$

$$I_{yaw} sr = -l_f \sum_{i=1}^{2} F_i + l_r \sum_{i=3}^{4} F_i. \tag{8}$$

Where M is vehicle weight, β is body slip angle, I_{yaw} is yaw inertia and s is Laplace operator.

B. Linear Suspension Roll Model

The roll motion equation is expressed by the following equation [12],

$$\begin{aligned} &-Mh_s V s\beta - I_{xz} s\gamma - Mh_s V\gamma \\ &+(I_{roll}s^2 + C_{roll}s + K_{roll} - Mgh)\phi = 0. \end{aligned} \tag{9}$$

where h_s is distance between CG and roll center (RC), I_{xz} is product of inertia, I_{roll}, C_{roll} and K_{roll} are inertia factors, damping factor and spring factor of roll motion, ϕ is roll angle.

Lateral acceleration on CG a_y is represented by the following equation using body side slip angle $\dot{\beta}$, yaw rate and vehicle velocity.

$$a_y = (s\beta + \gamma)V \tag{10}$$

Using eq. (10), the roll motion equation becomes:

$$\begin{aligned} Mh_s a_y & + I_{xz} s\gamma \\ & = (I_{roll}s^2 + C_{roll}s + K_{roll} - Mgh_s)\phi. \end{aligned} \quad (11)$$

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

$$\phi = \frac{Mh_s}{I_{roll}s^2 + C_{roll}s + K_{roll}} a_y. \quad (12)$$

In the next section, the rolling model parameters are identified by experimental result using a fixed trace method.

III. MODEL PARAMETER IDENTIFICATION

Rolling model parameters are identified by experimental results. The fixed trace method is applied for the identification [15]. From equation (12), lateral acceleration $\hat{y}$ is written as

$$\hat{y}(k|\theta) = \hat{\theta}^T \zeta(k). \quad (13)$$

Where $\theta = \left[\begin{array}{ccc} I_{roll} & C_{roll} & K_{roll} \end{array}\right]^T$, $\zeta = \left[\begin{array}{ccc} \ddot{\phi} & \dot{\phi} & \phi \end{array}\right]^T$.

FT method work as , when ζ is big and θ can be identified with good precision, and when ζ is small and not rich information and θ is seldom updated.

Update equation is written by the following equation.

$$\begin{aligned} \epsilon(k) &= y(k) - \hat{\theta}^T(k-1)\zeta(k), & (14) \\ \hat{\theta}(k) &= \hat{\theta}(k-1) + \frac{P(k-1)\zeta(k)}{1+\zeta^T(k)P(k-1)\zeta(k)}\epsilon(k), & (15) \\ P(k) &= \frac{1}{\lambda}(P(k-1) \\ & \quad - \frac{P(k-1)\zeta(k)\zeta^T(k)P(k-1)}{1+\zeta^T(k)P(k-1)\zeta(k)}), & (16) \\ \lambda &= 1 - \frac{|P(k-1)zeta(k)|}{1+zeta^T(k)P(k)\zeta(k)} \frac{1}{tr[P(0)]}. & (17) \end{aligned}$$

Where ϵ is output error, P is covariance matrix and λ is forgetting factor. Utilizing fixed trace method, angular frequency $w_n = \sqrt{\frac{K_{roll}}{I_{roll}}}$ is 17.2 (rad/sec) and damping coefficient $\zeta = \sqrt{\frac{1}{2I_{roll}K_{roll}}}C_{roll}$ is 0.234 (1/sec). Fig. 3 shows detected acceleration information by sensor and calculated acceleration by ζ and θ. From the figure, the two lines correspond and parameter identification is succeeded.

IV. ROLL STABILITY CONTROL BASED ON TWO-DEGREE OF FREEDOM CONTROL

A. *Following Capability with Feedback Controller*

Fig. 4 shows the block diagram of roll stability control based on basic feedforward and feedback control. Outside of dashed line corresponds to the real system and inside is vehicle controller. Roll moment M_{roll} is applied by differential torque of right and left in-wheel motors. Command value of roll rate is given by steering angle and vehicle velocity. The feedforward controller compensates system delay and improves stability of the system.

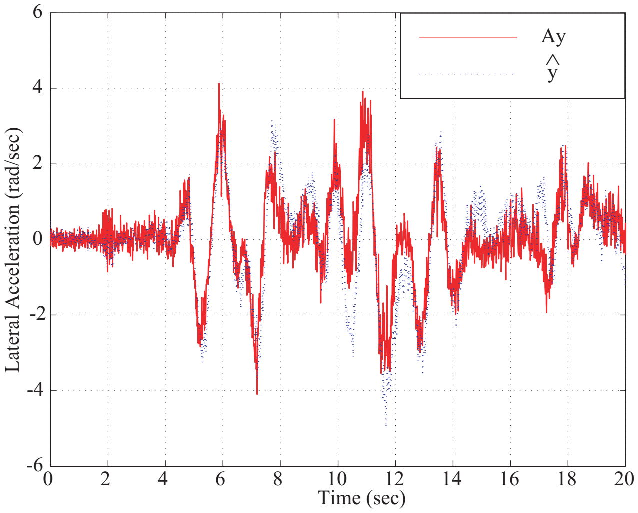


Fig. 3. Rolling model parameter identification

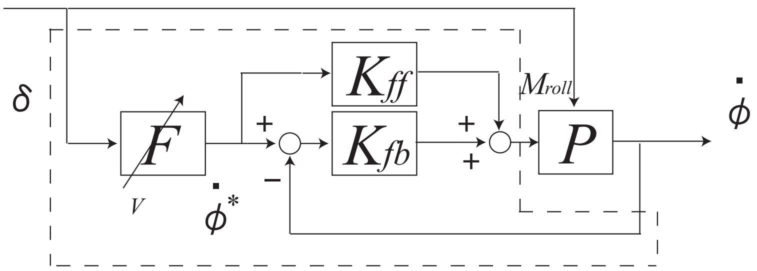


Fig. 4. Block diagram of roll stability control based on feedforward and feedback controller

B. *Robustness for roll moment disturbance*

In general, a combination of feedforward (FF) and feedback (FB) control is called two-degree of freedom control. However basic FF and FB controller cannot suppress disturbances. Hence two-degree of freedom control in the sense of following capability and disturbance suppression is proposed in this section. Proposed roll moment disturbance observer estimates external disturbance to the system with information such as vehicle velocity, steering angle, differential torque and roll rate. Fig. 5 shows the block diagram of roll moment disturbance observer.

Fig. 6 shows the proposed 2-DOF control for RSC. The observer loop is inside of the feedback and feedforward controller and it means disturbance observer response is relatively fast. Estimated roll moment disturbance is feedback to roll moment input.

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

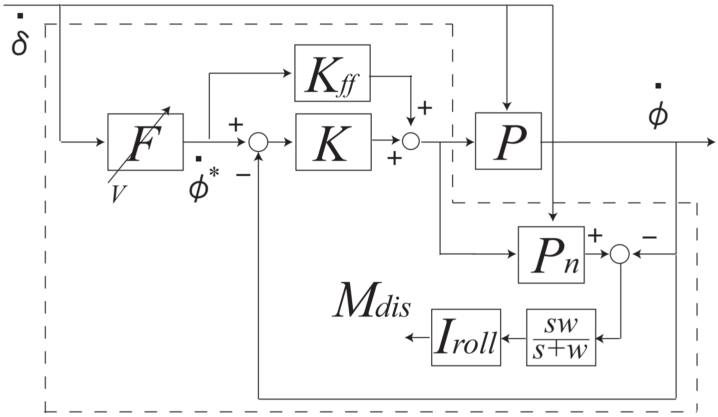


Fig. 5. Block diagram of roll moment disturbance observer

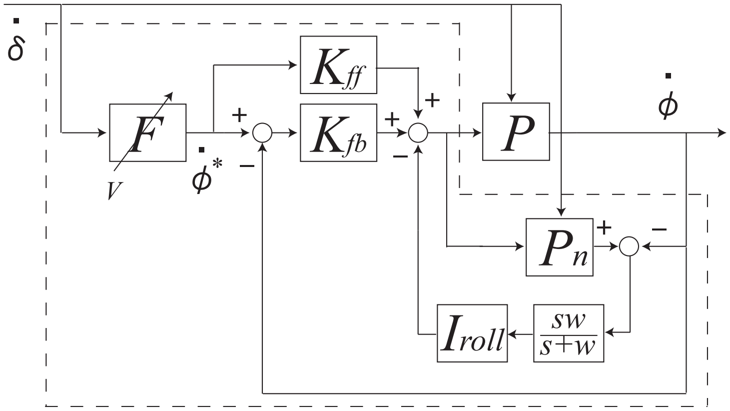


Fig. 6. 2-DOF roll moment control

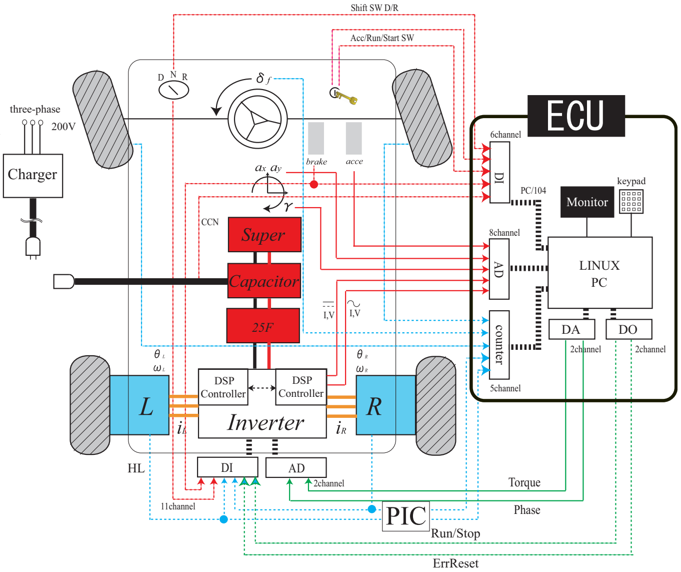


Fig. 7. Vehicle control system of experimental setup

TABLE I

DRIVE TRAIN SPECIFICATION OF EXPERIMENTAL SETUP

Motor	
Category	PSM
Phase/Pole	3/12
Rating power/Max	0.29kW/2kW
Max torque	100Nm
Max velocity	50km/h
Inverter	
Switching Hardware	MOS FET
Control method	PWM vector control
Energy storage	
Type	Electric double layer capacitor
Energy	100V, 83F, 144Wh

V. SIMULATION AND EXPERIMENTAL RESULTS

A. Experimental setup

A Novel one seater micro electric vehicle named ”Capacitor COMS1” is developed for vehicle motion control experiments. The vehicle equips two in-wheel motors for the rear tires, a steering sensor, an acceleration sensor and gyro sensors to detect roll and yaw motion. An upper micro computer collects sensor information with analog/digital converters and calculates command torques. System sampling time is 1 (msec). The command torque is input to the two in-wheel motors.

Fig. 7 shows the vehicle control system and TABLE I shows the specifications of the experimental vehicle.

B. Following capability of RSC

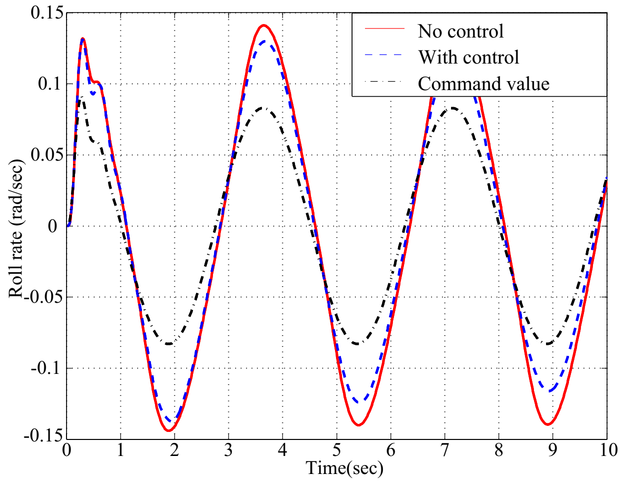
Fig. 8 shows simulation results of feedback control. The vehicle velocity is 4 (m/s) and steering input is 3 (Hz) sinusoidal wave. Roll rate is suppressed by differential torque on two rear electric motors. Since the system has torque limitation and mechanical delay, perfect tracking is impossible, even though, roll rate by sinusoidal steering input is effectively suppressed and controlled.

The following capability of RSC is demonstrated by the experiments in fig. 9. Reference roll rate $\dot{\phi}^*$ generated by steering angle and velocity information. The steering pattern is sinusoidal input and $\dot{\phi}^*$ is half of the nominal roll rate. With control, the peaks of roll rate and roll angle are suppressed.

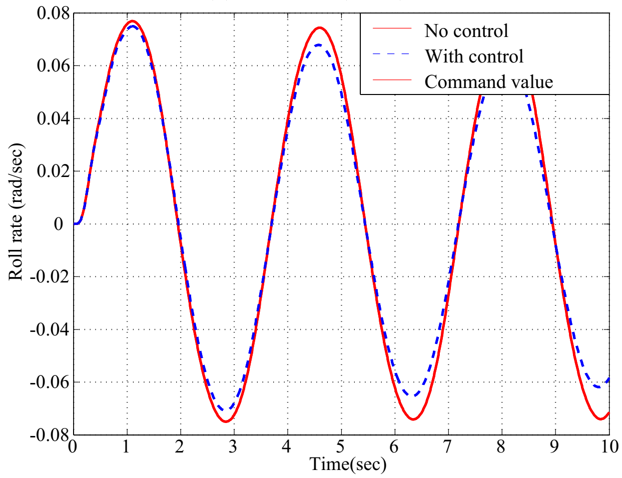
C. Disturbance suppression of RSC

In fig. 10, it is assumed that lateral blast, which is realized with sinusoidal wave in the simulation, is input to the vehicle at 5.3 (sec). With control, the proposed roll moment disturbance observer detects and suppresses the lateral disturbance. The robustness of 2-DOF is also verified by the experiment. The disturbance is applied to the system at 7.5 and 10.0 (sec). Here, the driver holds the steering straight. Compared to the no control case, the differential torque of motors effectively suppresses roll rate and roll angle.

The robustness of proposed 2-DOF control is verified through the experiments. Disturbance roll moment is also suppressed by differential torque. Fig. 11 shows the effectiveness of the proposed disturbance observer.

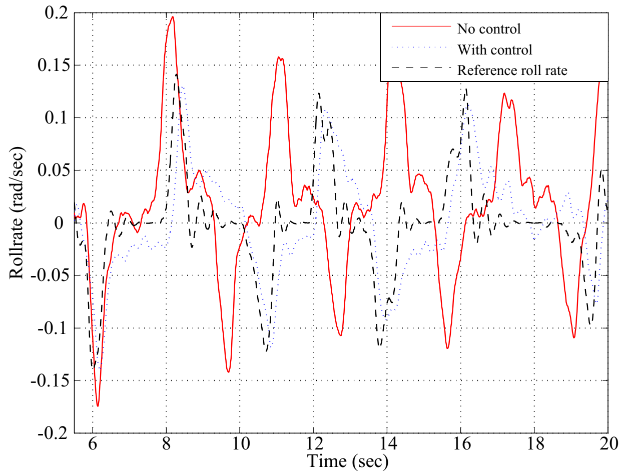


(a)Roll rate (rad/s)

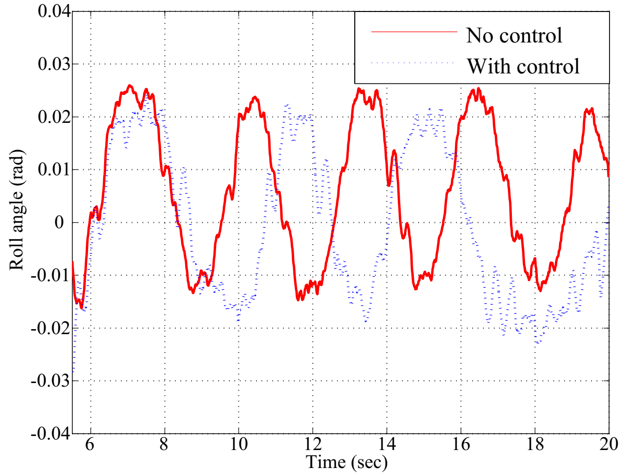


(b)Roll angle (rad)

Fig. 8. Simulation results of following capability of RSC



(a)Roll rate (rad/s)



(b)Roll angle (rad)

Fig. 9. Experimental results of following capability of RSC

VI. CONCLUSION

In this paper, a novel RSC on in-wheel electric vehicle is proposed utilizing teh electric motor's advantages. The RSC is important not only for ride quality but for safety as well. Sudden steering maneuvers can cause roll over especially in case of trucks. Although the RSC system has been developed by an automobile and several parts companies, they are controlling brake pad actuator which has time delay and cannot output positive torque. In this paper, the RSC is realized by motor actuators on in-wheel electric vehicle which have several advantages compare to internal combustion engine and brake actuators.

The four wheel model with nonlinear tire characteristic and linear roll suspension model are introduced in the second section. The Magic formula is applied for the tire model. In the third section, the rolling motion parameters are identified by using experimental result with fixed trace method. In the fourth section, the block diagrams of basic feedback control and proposed 2-DOF control for roll motion control are introduced. Simulation and experimental results verify the following capability for steering maneuver and the robustness for external disturbance of proposed RSC based on 2-DOF control.

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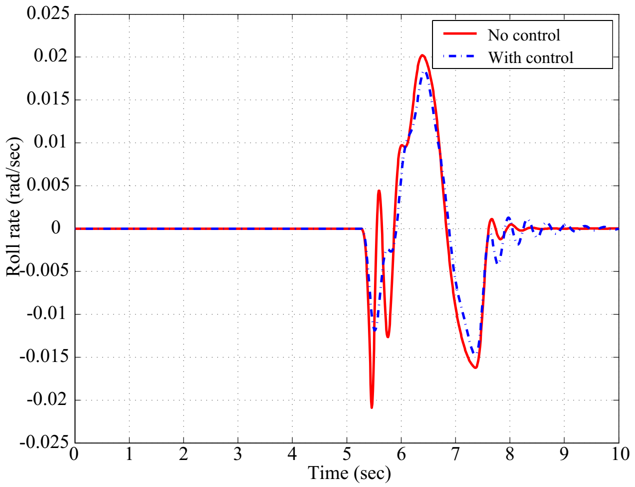
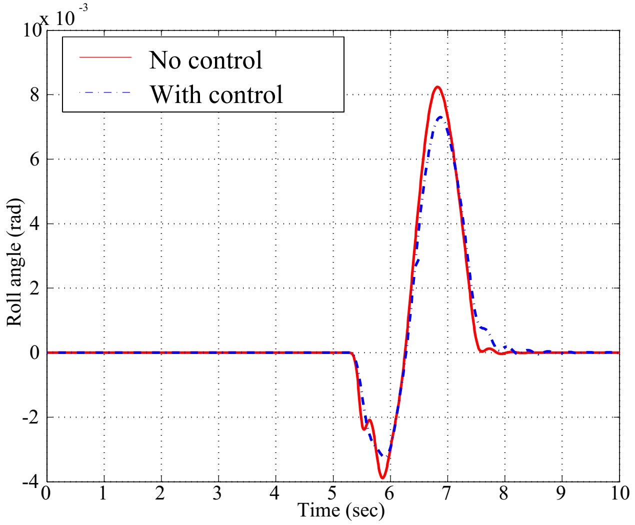
REFERENCES

[1] Kiyomoto Kawakami, Hidetoshi Tanabe, Hiroshi Shimizu, Hiroichi Yoshida, ”Advanced Redundancy Technology for a Drive System using In-Wheel Motors”, Electric Vehicle Symposium-22, pp.592-601, 2006

[2] 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, October 2004

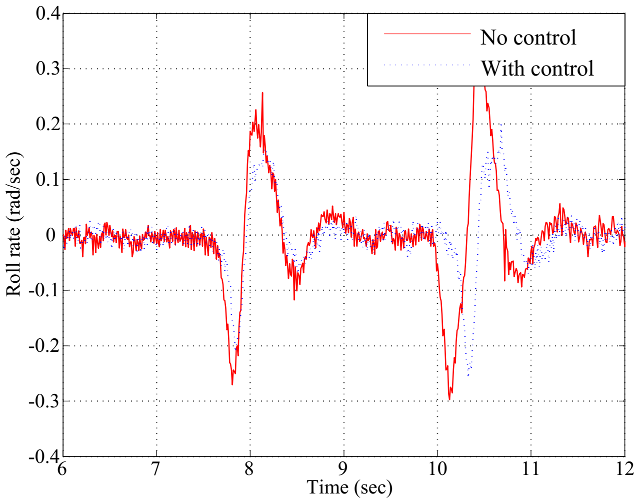


(a)Roll rate (rad/s)

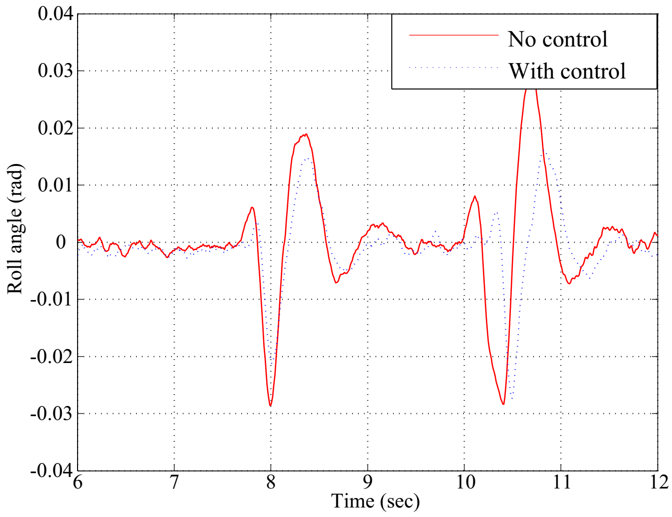


(b)Roll angle (rad)

Fig. 10. Simulation results of disturbance suppression of proposed RSC



(a)Roll rate (rad/s)



(b)Roll angle (rad)

Fig. 11. Experimental results of disturbance suppression of proposed RSC

[3] Shinichiro Sakai et al., Novel skid detection method without vehicle chassis speed for electric vehicle, JSAE Review, Vol.21, No.4, pp.504, 2000

[4] Hiroshi Fujimoto, Kiyoshi Fujii, Naoki Takahashi, Motion Control and Road Condition Estimation for Electric Vehicle, EVS-22, pp.1806-1817, 2006

[5] Hiroshi Fujimoto, Naoki Takahashi, Akio Tsumasaka, Toshihiko Noguchi, *Motion Control of Electric Vehicle Based on Cornering Stiffness Estimation with Yaw-moment Observer*, 9th IEEE International Workshop on Advanced Motion Control, Istanbul, pp. 206-211, 2006.

[6] Yoshifumi Aoki, Zhao Li, Yoichi Hori, Robust Design of Body Slip Angle Observer with Cornering Power Identification at Each Tire for Vehicle Motion Stabilization, The 9th International Workshop on Advanced Motion Control, 2006.3

[7] 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

[8] Leo Laine, Jonas Fredriksson, Traction and Braking of Hybrid Electric Vehicles using Control Allocation, Int. Journal of Vehicle Design, Special Issue on Advanced Traction/Braking Vehicle Control

[9] T. Brown, et al., Ford Global Technologies, Inc., Roll over stability control for an automotive vehicle. U.S. Patent. Patent No. 6324446

[10] H. Nakashima, et al., Aisin Seiki Co., LTD., Vehicle motion control system. U.S. Patent. Patent No. 5869943

[11] H. Nishizawa et al., Nisshinbo Industries, Inc., Braking force distribution control system and method. U.S. Patent. Patent No. 6276767

[12] Masato Abe, Vehicle dynamics and control (in Japanese), Sankaido, 1992

[13] Hans B. Pacejka, Tire and Vehicle Dynamics, pp. 34

[14] Hans B. Pacejka, Egbert Bakker, The Magic Formula Tyre Model, Vehicle System Dynamics International Journal of Vehicle Mechanics and Mobility, Vol. 21, No. 1, PP.1-18, 1992

[15] Yoichi Hori, Kohei Onishi, Advanced Control Engineering (in Japanese), Maruzen, 2000