Motor Torque Based Vehicle Stability Control for Four-wheel-drive Electric Vehicle

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***Abstract*—Motor torque based active yaw moment control law is investigated in this paper, based on which vehicle stability control algorithm for four-wheel-drive electric vehicle is proposed using fuzzy logic control method. As four motors are mounted in the four wheels individually to drive the vehicle, it has great advantage to use the advanced motion control technique to enhance vehicle stability. The four driving and braking forces can be controlled independently to generate active yaw moment. However it is more complex to allocate the desired yaw moment to over-actuators. So the control law for fuzzy logic control algorithm is designed based on the dynamic analysis of vehicle instability. The electric vehicle models including motor model, dynamic battery model, tire model and vehicle dynamics model are built in MATLAB/Simulink®. Simulation performance is evaluated in the Simulink®, and the results have shown that the design control law and fuzzy logic controller can enhance the yaw stability and improve the maneuverability of the vehicle significantly.**

Keywords-motor torque based; electric vehicle; vehicle stability control

I. INTRODUCTION

In recent years, due to the declining fossil resources and polluted environment, the new energy vehicle is developed urgently [1]. As a result, various electric vehicles are developed rapidly, such as electric vehicle and hybrid vehicle. And the performance of electric vehicles and corresponding components has improved remarkably. A large number of research projects carried out so far in regard to electric vehicle focused on performance improvement of their motors and batteries, and also a significant progress has been made in this field. However, a few studies are devoted to explore the potential of EV's advantage. Especially for motor mounted in wheel electric vehicle, it is more convenient to apply advanced vehicle stability control technique for enhancing active vehicle safety.

The advantages of the EV are summarized into three points [1]. The first one is the generated torque is very quick and accurate. And the second point is the motor torque can be measured easily, so the driving and braking force can be estimated in real time so that the observer technique can be applied easily. However, the most advantage is that four motors are installed in each wheel. Then the four wheels are independently driven by the four motors. What's more, the four motors can be not only the driving actuator but also the braking actuator, so each wheel can generate not only the same directional forces but also the rightabout forces, which is very significant for Active Yaw Moment Control (AYC). The active yaw moment can be generated more effectively to use the driving and braking forces.

The driving forces can be used to improve vehicle stability, but the vehicle yaw motion is more over-actuated. It is essential to determine how to use the actuators to generate yaw moment effectively. In the previous researches [2-3], the desired yaw moment is calculated firstly based on the error of actual vehicle states and desired vehicle states using the sliding mode control or fuzzy logic control. Then a hard nut to crack appeared: how to allocate the desired yaw moment to the actuators. One promising way to manage this problem is to use control allocation technique, which has been used successfully in aerospace vehicles [4-5], marine vessels [6]. But for ground vehicles there are many disturbances and the tire is even nonlinear and the tire longitudinal and lateral forces are coupled seriously. So it is very difficult to obtain good effectiveness in ground vehicles.

In this paper, the control law for four-wheel-drive electric vehicle is proposed based on the analysis of vehicle dynamic behavior and tire characteristic, based on which the fuzzy controller is designed. And the performance of this controller is evaluated in Simulink®.

II. SYSTEM MODELLING FOR EV

For the four-wheel-drive electric vehicle, both the vehicle dynamic model and dynamic powertrain systems such as the battery and motors are built in Matlab/Simulink®.

A. *Vehicle Dynamics Model*

The vehicle model used in this paper is a four-wheel-drive electric vehicle, only considering the planar motion: longitudinal, lateral, and yaw. And the vehicle is modeled as a rigid body with three-degree-of-freedom. The pitch and roll motions are ignored. Fig. 1 shows the vehicle diagram with planar motion.

We will assume that the driver controls the front wheel steering angle by using the steering wheel, while the controller can use the four longitudinal wheel slips for stabilizing the yaw motion. For electric vehicle, we assume that not only the braking forces but also the driving forces are available as control inputs.

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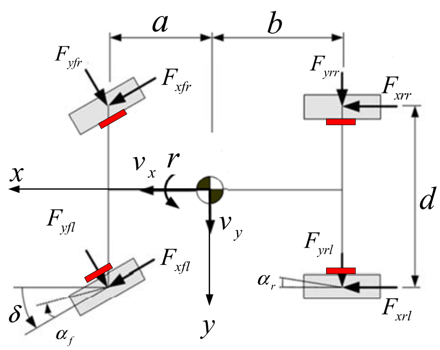


Fig. 1. Vehicle planar dynamic motion

The equation of motion for the vehicle dynamics can be written as,

$$m(\dot{v}_x - v_y r) = (F_{xfl} + F_{xfr})\cos\delta - (F_{yfl} + F_{yfr})\sin\delta + (F_{xrl} + F_{xrr}) \tag{1}$$

$$m(\dot{v}_y + v_x r) = (F_{yfl} + F_{yfr})\cos\delta + (F_{xfl} + F_{xfr})\sin\delta + F_{yrl} + F_{yrr} \tag{2}$$

$$I_z\dot{r} = (-F_{xfl}\cdot\cos\delta + F_{yfl}\cdot\sin\delta - F_{xrl} + F_{xrr} + F_{xfr}\cdot\cos\delta - F_{yfr}\cdot\sin\delta)\cdot\frac{d}{2} - (F_{yrl} + F_{yrr})\cdot b + ((F_{yfl} + F_{yfr})\cdot\cos\delta + (F_{xfl} + F_{xfr})\cdot\sin\delta)\cdot a \tag{3}$$

Where v_x is longitudinal vehicle velocity, v_y is lateral vehicle velocity, and r is yaw rate. F_x and F_y are longitudinal and lateral tire forces. The abbreviation *fl*, *fr* is front left, front right and *rr*, *rl* is rear right, rear left. The front and rear tire slip angles α_f and α_r are average slip angles of left and right wheels. δ is steering angle input. a and b are distances from center of gravity to front and rear axle, d is track width. And m represents vehicle mass, I_z is moment of inertia about yaw axis.

B. Tire Model

The tire model needs to describe the dependencies of the tire force on the slip/slip angle, friction coefficient as well as the interaction between longitudinal and lateral forces. So we applied the well-known Pacejka Magic Formula tire model. The tire model formulas can be written as,

$$y = D\sin(C\arctan\{Bx - E[Bx - \arctan(Bx)]\}) \tag{4}$$

with $Y(X) = y(x) + S_V$, $x = X + S_H$

Where Y represents the output variable, which can be longitudinal force F_x or lateral force F_y. X is the input variable, which can be slip angle α or longitudinal slip λ. The coefficients B, C, D and E are the stiffness factor, the shape factor, the peak value and the curvature factor respectively. H B, C, D, E, S_H and S_V are known as primary Magic Formula parameters.

C. Traction Motor Dynamic Model

The traction motor [7] extracts power from the battery, and provides torque to the driveline, which in turn provides the EV motive power. Additionally, the traction motor and controller is also operated as an alternator combination and as a generator used to recover the vehicle kinetic energy dissipated during braking. The traction motor and controller then provide power to the battery, and negative torque to the driveline, which in turn brakes the vehicle.

Since the motor torque dynamics is very fast compared with other powertrain elements dynamics, the motor torque dynamics is modeled by a second order system as

$$G(s) = \frac{T_m}{T_{m\_desired}} = \frac{1}{1 + 2\xi s + 2\xi^2 s^2} \tag{5}$$

Where $T_{m\_desired}$ is the desired motor torque, ξ is the motor torque time constant.

D. Battery Dynamic Model

The battery is operated as energy storage. When traction force is needed, the battery provides energy to driveline for driving the vehicle. And when braking, the energy is recovered to battery.

According to [9], the battery is modeled using a simple controlled voltage source in series with a constant resistance. This model assumes the same characteristics for the charge and the discharge cycles. The open voltage source is calculated with a non-linear equation based on the actual *SOC* of the battery. The controlled voltage source is described as,

$$E = E_0 - K\frac{Q}{Q - \int idt} + A\exp(-B * \int idt) \tag{6}$$

Where, E is no-load voltage (V), E_0 is battery constant voltage (V), K is polarization voltage (V), Q is battery capacity (Ah), $\int idt$ is actual battery charge (Ah), A is exponential zone amplitude (V), B is exponential zone time constant inverse ($(Ah)^{-1}$).

The battery voltage is,

$$V_{batt} = E - R * i \tag{7}$$

Where, V_{batt} is battery voltage (V), R is internal resistance (Ω), i is battery current (A).

It was shown that [9] this model can accurately represent the discharge curves of the manufacturers and it has been inserted in Simulink® Package.

III. Control Law

Active yaw moment control is very effective to stabilize vehicle yaw motion when the sideslip angle and/or acceleration are higher and the nonlinearity of the tire and vehicle dynamics is taken into consideration [10]. However, in this condition there is a hard nut that how to control the four wheels forces to generate active yaw moment effectively, especially when both the traction and braking forces can be used to generate yaw moment. In this paper, the control law is investigated based on vehicle instability analysis and the nonlinearity and coupling of the tire.

A. Vehicle Instability Analysis

When a car is running on the thruway in high speed, there are two typical styles of instability: under steer and over steer, as shown in Fig. 2.

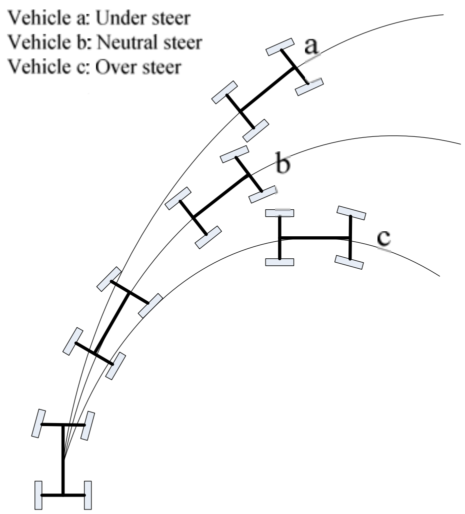


Fig. 2. Under steer and over steer

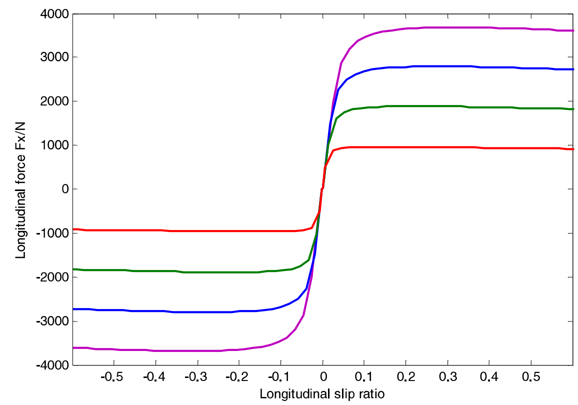
Under steer is when the slip angle of front wheel is greater than the slip angle of the rear wheel. The front wheels are carving a larger arc than the rear wheels. This is because the front wheels lose adhesion before the rear wheels, causing the front wheels to push toward the outside of the curve, resulting the vehicle "drifting out", as vehicle a Fig.2.

And over steer (vehicle c in Fig.2) is when the slip angle of the rear wheels is greater than the slip angle of the front wheels. The rear wheels are carving a larger arc than the front wheels. This trends cause the vehicle to spin in a high speed, and even to roll over.

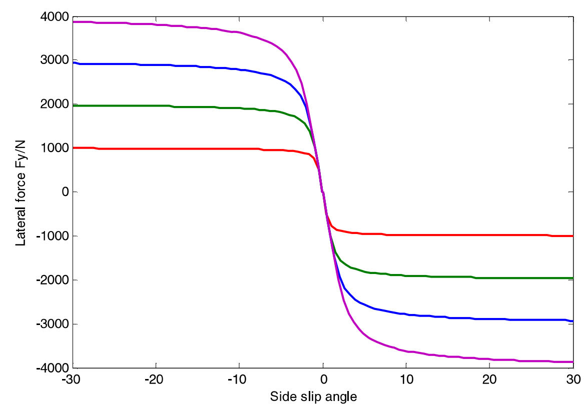
In the thruway, lots of accidents are caused by these two instabilities [11]. Sometimes the drivers turn the steering wheel hurriedly to avoid the obstacle in the road, and again turn the steering wheel rapidly to return to the primary track, causing the vehicle unstable and out of control, in which condition the over steer and under steer are always both appeared. Hence, for vehicle stability control system, the main function is to control the vehicle to avoid under steer and over steer.

B. Tire Characteristic

The tire forces are the main resource of vehicle motion, and they are the sole outer forces which can be controlled to obtain anticipant vehicle motion. When the slip ratio or slip angle is bigger, the tire forces characteristic presents even nonlinearity. And when the wheel is cornering, the longitudinal force and the lateral force are coupled severely. So, in order to make full use of the wheel forces, the tire force characteristic is observed and understood essentially.



(a) Tire longitudinal forces



(b) Tire lateral forces

—F_z=4000; —F_z =3000; —F_z =2000; —F_z =1000;

Fig. 3. Tire forces characteristic

In Fig. 3, if the longitudinal or lateral tire force is generated individually, the longitudinal or lateral force increases as the slip ratio or slip angle aggrandizes. But, when they exceed the given value of the slip ratio or slip angle, the forces will stop increasing, and even the declining phenomena appear. This is also why ABS/TCS is used. It can also be seen in Fig.3 that the longitudinal force and lateral force are even sensitive to the normal force. When the normal force is too small, the tire will have less capability to generate longitudinal force and lateral force.

When a car is turning and braking or accelerating at the same time, tires are often expected to generate lateral and longitudinal forces simultaneously as big as expected. However, the actual situation is not favorable due to the interaction between lateral and longitudinal forces. The maximum lateral force is achieved when there is no longitudinal force and, conversely, the maximum longitudinal force is achieved when the lateral force is zero.

Assuming a constant normal force, the maximum tire forces are essentially limited to a circle in the *Fx-Fy* plane, which is called friction circle [12], shown in Fig.4.

From the friction circle, it can be obtained that the maximum lateral force that a tire can generate is reduced as it is required to simultaneously generate braking or traction forces, at the same time, the maximum braking and traction force that a tire can generate is reduced in a cornering situation in which a lateral force must be produced simultaneously.

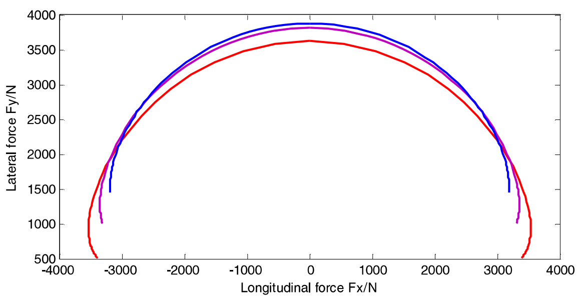
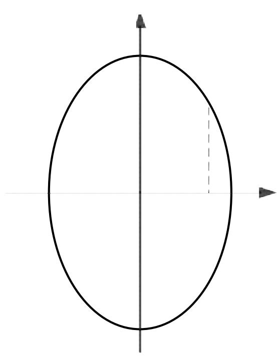


Fig. 4. Tire friction circle

And when the tire generates the maximum lateral force in a cornering situation the longitudinal force is generated, the lateral forces will be reduced inevitably, which can also be seen in Fig.4.

As shown in Fig.5, under the constant normal force, the tire can generate a maximum force which is shown as F_{max1} . A lateral force F_{ya} is generated for cornering, and at the same time a longitudinal force is generated. Before the longitudinal is less than F_{xa}, the lateral force will not be affected. But after it exceeds F_{xa}, the lateral force will reduce as the longitudinal force increases. And if normal force is smaller, the maximum force generated will be small consequently, shown as F_{max2} and $F_{max3.}$



desired vehicle motion based on the driver commands. The yaw moment controller compares the actual vehicle motion and the desired vehicle motion, and provides the desired yaw moment. The module of yaw control allocation determines the longitudinal slip ratio for each tire based on the control law. The ABS/TCS system which is assumed to be available is to manipulate braking torque and wheel traction to track the desired longitudinal slip ratio calculated by control allocation, and to generate an actual yaw moment and exert itself to satisfy the desired yaw moment. The actual vehicle model affected by this yaw moment provides corresponding actual vehicle motion and feed it back to the vehicle state observer, which estimate the actual motion of the vehicle.

B. *Fuzzy Logic Controller*

When the vehicle is cornering in a high speed, the nonlinearity of the tire and vehicle dynamics presents severely. In order to enhance the robustness of the controller, fuzzy logic control is applied. For the vehicle stability controller, two fuzzy controllers are designed. Firstly the yaw moment controller is designed to calculate the desired yaw moment based on the error of the yaw rate and the sideslip angle. And then based on the desired yaw moment the desired slip ratios for all wheels are obtained using the control allocation fuzzy controller.

The inputs of the yaw moment fuzzy controller are the errors of the vehicle yaw rate and sideslip angle. The error is defined as the difference between the desired values calculated based on the desired vehicle motion and the actual values from the actual vehicle model. The desired yaw moment is obtained according to the basic rule of the characteristic of the under steer and over steer.

The fuzzy yaw moment controller consists of a triangular membership function. The input rule base consists of the 5 linguistic variables such as NB (negative big), NS (negative small), ZO (zero), PS (positive small), PB (positive big) and is arranged by the center of gravity method. Membership of the output variable has nine linguistic values, described as N (negative), NB (negative big), NM (negative middle), NS (negative small), ZO (zero), PS (positive small), PM (positive middle), PB (positive big), P (positive). The rule base for the controller is shown in Table 1.

TABLE I. FUZZY CONTROL RULE FOR DESIRED YAW MOMENT

Active yaw moment		Side slip angle error				
		NB	NS	ZO	PS	PB
Yaw rate error	NB	N	NB	NM	NS	NS
	NS	NB	NM	NS	PS	PS
	ZO	NM	NS	ZO	PS	PM
	PS	NB	PS	PS	PM	PB
	PB	PS	PS	PM	PB	P

Based on the calculated desired yaw moment, the slip ratio for every wheel is obtained using the control allocation fuzzy controller, which consists of a triangular membership function. The input rule base consists of the 9 linguistic variables as the output of yaw moment controller. The outputs are the desired slip ratio for every wheel. The output variables are uniformed as NB (negative big), NS (negative small), ZO (zero), PS (positive small), and PB (positive big), which are arranged by the center of gravity method. The rule base for the controller is shown in Table 2.

TABLE II. FUZZY CONTROL RULE FOR SLIP RATIO

Active yaw moment	Slip ratio			
	Front Left	Front Right	Rear Left	Rear Right
N	PB	NB	ZO	ZO
NB	PS	NB	ZO	ZO
NM	ZO	NB	ZO	ZO
NS	ZO	NS	ZO	ZO
ZO	ZO	ZO	ZO	ZO
PS	ZO	ZO	NS	ZO
PM	ZO	ZO	NB	ZO
PB	ZO	ZO	NB	PS
P	ZO	ZO	NB	PB

For motor-in-wheel electric vehicle, to generate the active yaw moment, the electric motor can be applied not only as the traction actuator but also the braking actuator. And the forces needed are always not so big, so the hydraulic braking system is not applied in this paper, in order to investigate the effectiveness of the traction motor. Besides, considering the recapturing energy, the desired yaw moment is generated by the electric motor regenerative braking force in priority.

V. SIMULATIONS

In order to demonstrate the advantages of the control law and the active yaw moment control for the four-wheel-drive electric vehicle. We designed the vehicle stability controller in Matlab/Simulink® based on the control law described above.

When the vehicle is running on the low fiction road at speed 80km/h, a lane change maneuver is implemented. The responses of vehicle with four-wheel-drive electric vehicle ESP (EV ESP) are compared with those of conventional ESP and without any control. The steering angle of front wheel is shown in Fig. 7.

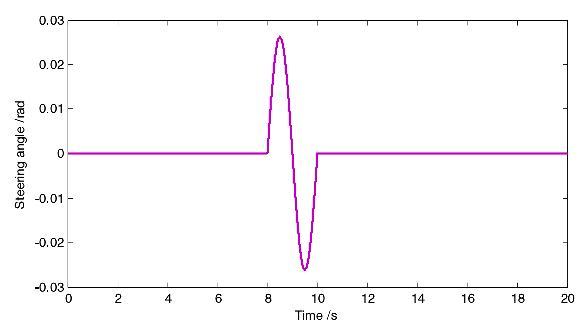


Fig. 7. Steering angle

As shown in Fig.8 and Fig.9, the EV ESP can enhance the vehicle stability significantly as the conventional ESP. However, the prominent advantage of EV ESP is the reduction of the vehicle speed is even less than that of conventional ESP, as shown in Fig.10. Hence, vehicle mobility and agility are also improved by EV ESP. Due to the braking system is the actuator of conventional ESP, the vehicle speed will be reduced when it is actuated, which is not suitable for normal condition when not the safety rather the vehicle maneuverability is most concerned. But in critical condition the stability and safety are the control focus, the conventional ESP is still preferential. So the EV ESP is suitable for integration chassis control system, which can achieve not only safety enhancement but also maneuverability improvement.

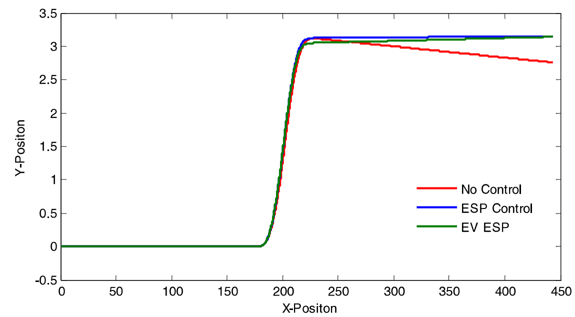


Fig. 8. The position of vehicle

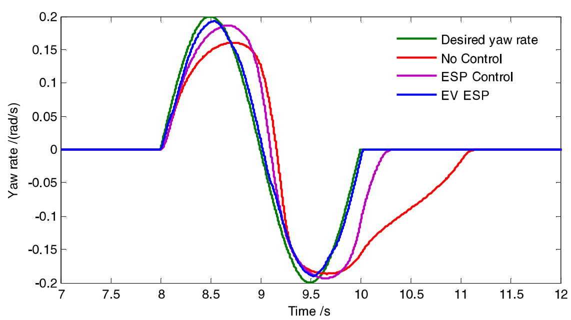


Fig. 9. Yaw rate response

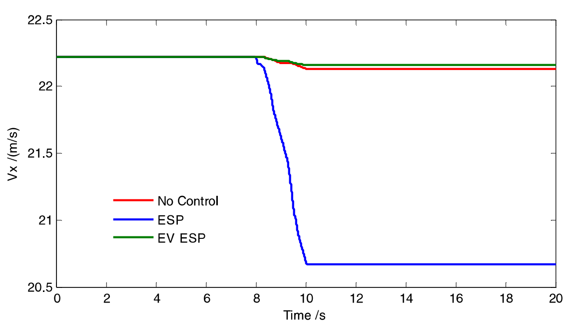


Fig. 10. Vehicle speed

ACKNOWLEDGMENT

The authors would like to thank Mohanad El-Haji, the colleague in the department of vehicle technology and mobile machines at the Karlsruhe Institute of Technology (KIT) for his sincerely advise and language emendation. Also they would like to thank Prof. Frank Gauterin, the mentor of Li Feiqiang in Germany for the support of research.

VI. CONCLUSIONS

The four-wheel-drive electric vehicle powertrain model and nonlinear vehicle dynamic model are established in this paper. According to the advantage of mounted in wheel traction motor and analysis of vehicle instability and tire characteristic, a new vehicle stability enhancement strategy is proposed. Based on this control strategy, the vehicle stability controller is designed based on the fuzzy logic control technique. Simulation results in Simulink® have shown that the proposed controller not only enhances vehicle stability but also improves vehicle maneuverability.

REFERENCES

[1] Yoichi Hori, Future Vehicle Driven by Electricity and Control-Research on Four-Wheel-Motored “UOT Electric March II ”. IEEE TRANSACTIONS ON INDUNSTRIAL WLECTRONICS, VOL.51, NO.5, OCTOBER 2004

[2] Kim D H, Kim J M, Hwang S H, “Optimal brake torque distribution for a four-wheel-drive hybrid electric vehicle stability enhancement”, Proceedings of the Institution of Mechanical Engineers Part D-Journal of Automobile Engineering, 2007, 221(D11): 1357-1366

[3] Shuen Zhao, Yinong Li, Ling Zheng and Shaobo Lu, Vehicle Lateral Stability Control Based on Sliding Mode Control, Proceedings of the IEEE International Conference on Automation and Logistics, Jinan, China, August 18-21,2007:638-642

[4] John J. Burken, Ping Lu, Zhenglu Wu, and Cathy Bahm. Two reconfigurable flight-control design methods: Robust servomechanism and control allocation. Journal of Guidance. Control, and Dynamics, 24(3):482-493, May-June 2001.

[5] Wayne C. Durham. Constrained control allocation: Three-moment problem. Journal of Guidance, Control, and Dynamics, 17(2):330-337, March-April 1994.

[6] Thor I. Fossen Tor A. Johansen and Svein P. Berge. Constrained nonlinear control allocation with singularity avoidance using sequential quadratic programming. IEEE Trans. Control Systems Technology, 12,2004.

[7] K.E. Bailey and B.K. Powell, A HYBRID ELECTRIC VEHICLE POWERTRAIN DYNAMIC MODEL, Proceedings of the American Control Conference Seattle, Washington, June 1995:1677-1682

[8] Geoffrey May, BATTERY OPTIONS FOR HYBRID ELECTRIC VEHICLES, Hybrid Vehicle Conference, The Institution of Engineering and Technology, 2006, 12-13 Dec. 2006 Page(s):67 – 78

[9] Tremblay, O., Dessaint, L.-A., Dekkiche, A.-I., A Generic Battery Model for the Dynamic Simulation of Hybrid Electric Vehicles, Vehicle Power and Propulsion Conference, 2007. VPPC 2007. IEEE 9-12 Sept. 2007 Page(s):284 – 289

[10] YOSHIMI FURUKAWA, MASATO ABE, Advanced Chassis Control Systems for the Vehicle Handling and Active Safety. Vehicle System Dynamics, 28(1997), pp.59-86

[11] Van Zanten A T. “Bosch ESP Systems: 5 Years of Experience”. SAE Paper, NO.2000-01-1633, 2000.

[12] Milliken W F, Milliken D L. Race car vehicle dynamics. Society of Automotive Engineers. SAE books, ISBN 1-56091-529-9, 1995

[13] Li Feiqiang, Wang Jun, Liu Zhaodu. On the Vehicle Stability Control for Electric Vehicle Based on Control Allocation. IEEE Vehicle Power and Propulsion Conference (VPPC), September 3-5, 2008.