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Integrated Control Strategy for Torque Vectoring and Electronic Stability Control for in wheel motor EV

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Abstract

With the recent advancement of control method and battery technology, the electric vehicle has been researched to replace the conventional vehicle with electric vehicle with the view point of the environmental concerns and energy conservation. An electric vehicle which is equipped with the in-wheel motors has some advantages in terms of control. For example, the different torque which generated by left and right wheels directly can make yaw moment of vehicle with steering angle and it can improve the vehicle stability in cornering. In this paper, we consider a method for improving the stability and manoeuvrability of In-wheel motor electric vehicle with the torque vectoring and electronic stability control (ESC). We created a mathematical model for torque vectoring, ESC and vehicle dynamics and determined operation range of torque vectoring and ESC using value of difference between yaw rate and desired yaw rate. Simulation results show that the method can improve the stability and manoeuvrability of In-wheel motor electric vehicle in cornering

Key word : In wheel driven EV, Torque vectoring, Electronic stability control, manoeuvrability, stability, Integration control

1 Introduction

Recently, many automakers are putting in efforts to develop the next generation electric propulsion systems for EVs (electric vehicle), Plug-in HEVs (hybrid electric vehicle) and FCVs (fuel cell vehicle). Electric propulsion as the main power source in vehicles can be divided into two categories. The first is the currently manufactured type in which a single motor is mounted on the center of the chassis by replacing the internal combustion engine and the power is transmitted to the wheels through the drivetrain (transmission, differential, drive shaft, and the universal joints). The second category is a more innovative system in which independent in-wheel motors are installed in each wheel and the power from the motors are transmitted directly to the wheels without any shafts [1].

In-wheel vehicles have the benefits of more interior space, design freedom, lower center of gravity, improved weight balance, greater fuel economy, and better vehicle stability [2] since the drive and brake torque can be controlled independently at each wheel via electric torque vectoring control using the torque difference between the left and right wheels. On the other hand, in-wheel motor vehicles have technical challenges to be resolved such as 1) wheel assembly package including suspension, steering, and brake, 2) durability and reliability of mechanical parts, 3) motor cooling performance, and 4) increased unsprung mass effect.

These direct yaw moment control methods are based on the advantages of electric vehicle with in-wheel motor and improve the performance of the electric vehicle. The driving system with in-wheel motor has the following advantages in terms of control [3]:

1) Quick and accurate torque generation

2) Easy torque calculation

3) Independent torque control

A torque distribution method based on direct yaw moment control algorithm improves a cornering performance of electric vehicle.
In this paper, torque vectoring and electronic stability control (ESC) are proposed to improve cornering performance of rear wheel driven in wheel motor electric vehicle. Yaw moment is calculated using control algorithm of yaw rate and desired yaw rate. ESC determines break pressure of 4 wheel and torque vectoring determines rear wheel driven torque using yaw moment. Torque vectoring and ESC are operated by operation range which is determined by value of difference between yaw rate and desired yaw rate. For example, if value of difference between yaw rate and desired yaw rate is so small, only torque vectoring operates to improve cornering performance, and if value of difference between yaw rate and desired yaw rate is so big, ESC operates to vehicle stability.

2 Vehicle modelling

A bicycle model is used for the controller design in this paper. The equations of motion can be expressed as follows.

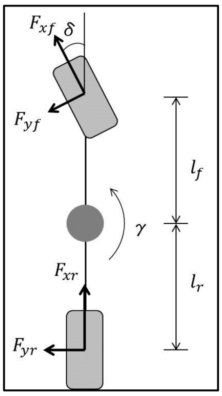


Figure1: 2-DOF vehicle model

$$I_z\dot{\gamma} = l_f F_{yf}\cos\delta - l_r F_{yr} + M_z \quad (1)$$

where γ is the yaw rate, I_z is the yaw moment of inertia, F_{yf} and F_{yr} are the front and rear lateral tire forces respectively, l_f and l_r are the distance from vehicle center of gravity (CG) to front and rear axles, δ is the front steering angle, and the yaw moment M_z indicates a direct yaw moment control input, which is generated by the independent torque control of in-wheel motors and is used to stabilize the vehicle motion.

3 Controller design

A reference generator makes a desired yaw rate γ_d from driver's steering command δ_{cmd} and vehicle speed V_x. The feedback controller is designed to make yaw moment(M_z) to compensate yaw rate tracking error ($\gamma_d - \gamma$) based on the standard sliding mode control methodology.

3.1 Decision of desired yaw moment using a sliding mode control law

It is well known that sliding mode control is a robust control method to stabilize nonlinear and uncertain systems which have attractive features to keep the systems insensitive to the uncertainties on the sliding surface [4]
The objective of controller is to determine the desired yaw torque for the vehicle so as to track the desired yaw rate. The equations of desired yaw rate can be expressed as follows.

$$\gamma_{des} = \frac{V_x}{l_f + l_r + \frac{m{V_x}^2(l_r C_{ar} - l_f C_{af})}{2C_{af}C_{ar}L}}\delta \qquad (2)$$

The sliding surface is chosen so as to achieve either yaw rate tracking. The sliding surface can be expressed as follows.

$$\text{s} = \gamma - \gamma_{des} \qquad (3)$$

Condition of s=0 can be expressed as follows.

$$\begin{aligned}\dot{s} &= -\eta s = \dot{\gamma} - \dot{\gamma}_{des} \\ &= \frac{1}{I_z}(l_f F_{yf}\cos\delta - l_r F_{yr} + M_z) - \dot{\gamma}_{des} \qquad (4)\end{aligned}$$

3.2 Design of torque vectoring controller

Torque of each wheel is determined by M_z generated by sliding mode control and vehicle parameters.

$$F_{xl} = \frac{T_m + \Delta T}{r \cdot r_{ratio}}, \quad F_{xr} = \frac{T_m - \Delta T}{r \cdot r_{ratio}} \tag{6}$$

$$M_z = -F_{xl} \cdot \frac{t}{2} + F_{xr} \cdot \frac{t}{2} \tag{7}$$

$$\Delta T = \frac{2r \cdot r_{ratio}}{t} M_z \tag{8}$$

Where F_{xl} and F_{xr} are the front and rear longitudinal tire forces, T_m is generated motor torque, and r is radius of tire. r_{ratio} is constant about radius of tire, it use to convert from motor torque to longitudinal force. t is vehicle trade.

3.3 Design of ESC controller

ESC controller determines the break torque at each wheel, so as to provide a net yaw moment that track the desired value for yaw moment.

$$M_z = -F_{xfl} \cdot \frac{t}{2} + F_{xfr} \cdot \frac{t}{2} \tag{9}$$

$$\Delta F_{xf} = \frac{2M_z}{t} \tag{10}$$

$$T_{desired\_brake} = r \cdot \Delta F_{xf} \tag{11}$$

3.4 Strategy of integrated control

Operating time of torque vectoring and ESC should be determined as driving environment to improve cornering performance. Proposed torque vectoring logic and ESC logic are simulated by applying various driving conditions to analyze these system features. These analysis results are used develop integrated control logic and control strategies.

3.4.1 Simulation of Torque Vectoring, ESC

Developed torque vectoring and ESC of control logic of are analyzed by using Matlab, Simulink and Carsim to analysis features of these systems.
Hatchback A-Class vehicle provided by the CarSim software is used as the test vehicle. The transmission and engine system of test vehicle is removed to make a rear wheel drive electric vehicle with in-wheel motor.

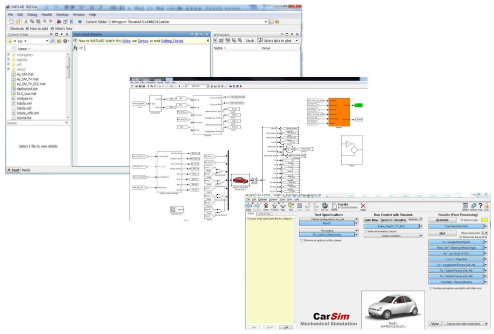


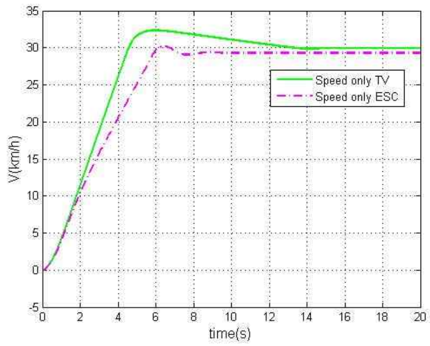
Figure 2: Analysis S/W

Simulation conditions are circular road and J-turn, detail conditions is table 1 is shown detail simulation condition.

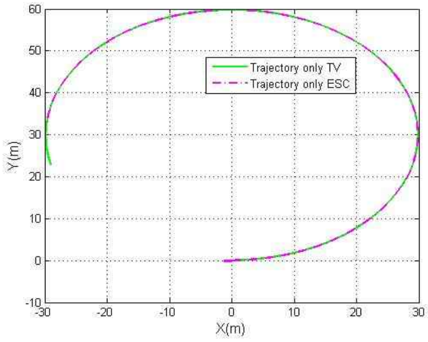
Table1: Simulation environment

Condition of steering	Speed(kph)		
Constant(circle road)	0→30	0→60	
J-turn(90 deg)	30	60	80

Only ESC logic applied model does not follow the required speed at low speed condition or stable state because ESC makes the vehicle slow down to follow the desired yaw moment. So, result of trajectory shows that driving distance of only ESC logic applied model is shorter than only torque vectoring logic applied model.
Figure 3, Figure 4 are simulation result at circular road(0→30kph) and J-turn(30kph).

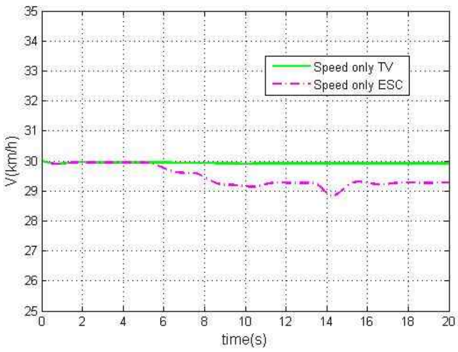


(a) Speed at circular road(0→30kph)

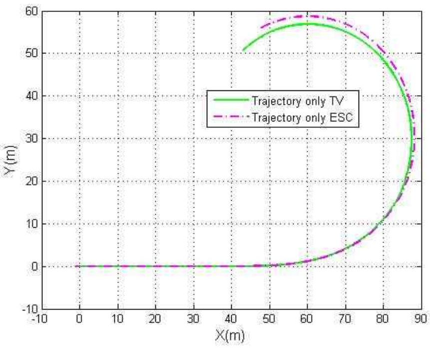


(b) Trajectory at circular road(0→30kph)

Figure3: circular road(0→30kph) simulation result



(a) speed at J-turn(30kph)

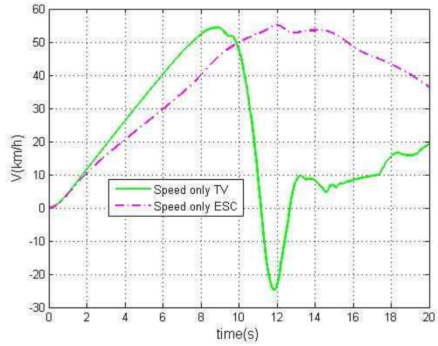


(b) Trajectory at J-turn(30kph)

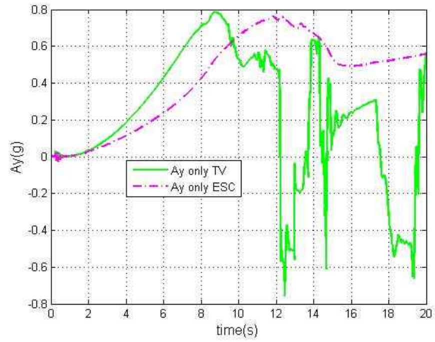
Figure4: Circular road simulation result

When vehicle speed and lateral acceleration are increasing, Dirving trajectory of only torque vectoring logic applied model break away from desired path on circular road and J-turn because of increasing lateral acceleration. Only ESC logic applied model break away from desired path, but point of unstable of vehicle dynamics and point of leaving path are delayed because of decreasing vehicle speed.

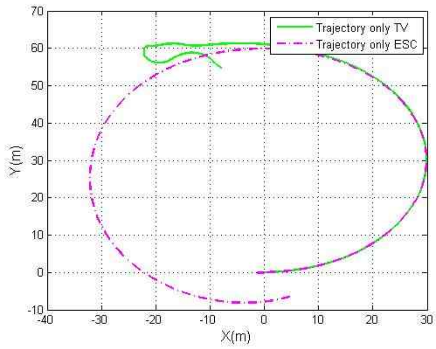
Figure 5, Figure 6 are simulation result at circular road(0→60kph) and J-turn(80kph).



(a) Speed at circular road (0→60kph)

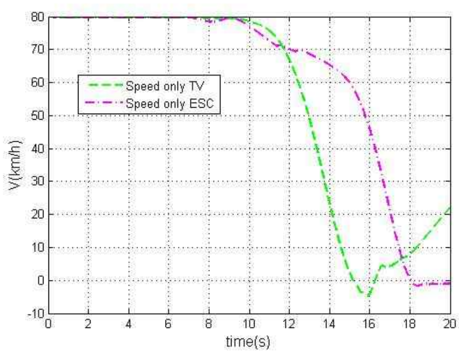


(b) Lateral acceleration at circular road (0→60kph)

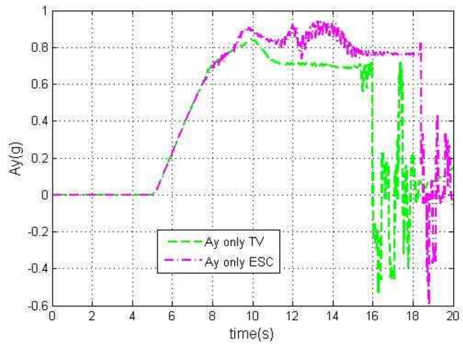


(c) Trajectory at circular road (0→60kph)

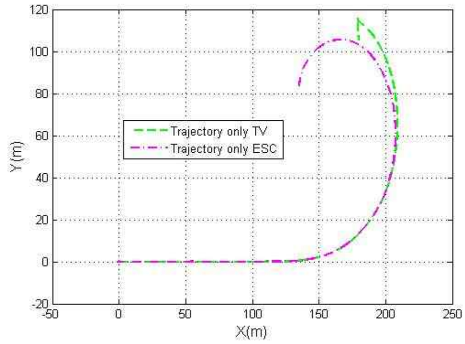
Figure5: circular road (0→60kph) simulation result



(a) speed at J-turn(80kph)



(b) Lateral acceleration at J-turn(80kph)



(c) Trajectory at J-turn (80kph)
Figure6: J-turn (80kph) simulation result

When vehicle speed is low or vehicle state is stable, torque vectoring assist to improve the cornering performance. And when vehicle speed is fast or lateral acceleration is high, decreasing vehicle speed as operating ESC assist to improve the cornering performance.

3.4.2 Design of integrated controller

Integrated control strategy separate 3 region. To divide 3region, We simulated a variety of driving conditions. And we can obtain value of yaw rate at variety driving condition. Yaw-rate error is difference value outputted yaw rate at vehicle model and calculated desire yaw-rate. Yaw-rate error values is analysed as driving condition. And region of stable, unstable and Extremely unstable are divided into e_1 and e_2.

$$|\gamma - \gamma_{des}| = yaw - rate \quad error \quad = e \qquad (12)$$

$$\text{Vehicle is stable} \quad \text{if} \quad e < e_1$$

$$\text{Vehicle is unstable} \quad \text{if} \quad e_1 \leq e \leq e_2 \qquad (13)$$

$$\text{Vehicle is extreme unstable} \quad \text{if} \quad e_2 > e$$

Fig.7 shows operating ESC and torque vectoring as value of e_1 and e_2.
When vehicle is stable, only torque vectoring affect vehicle stability. If a vehicle is unstable, torque vectoring and ESC intervene to stabilize cornering performance. If state of vehicle is extremely unstable, only ESC operate to reduce vehicle speed.

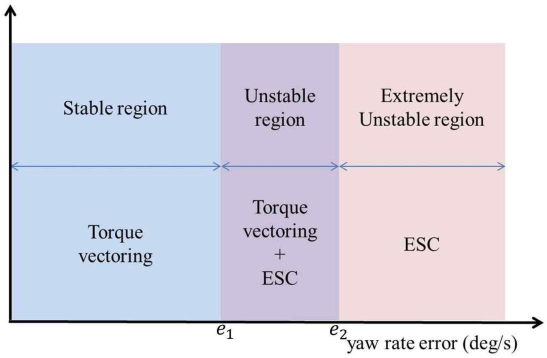


Figure7: Operation range distribution of integrated controller

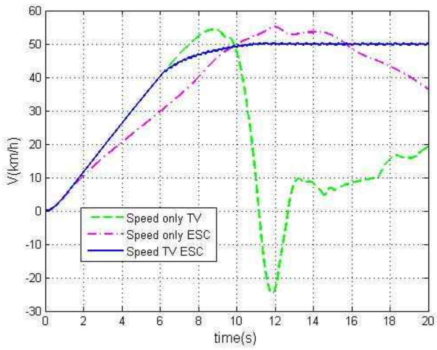
4 Simulation result

Circular road and J-turn are used to integrated control performance analysis.
Table 2is detail simulation condition.

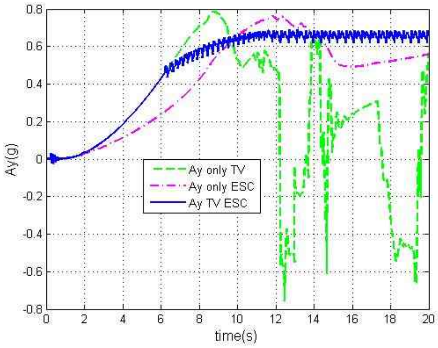
Table2: Simulation condition

Condition of steering	Speed(kph)
Constant(circle road)	0→60
J-turn(90 deg)	80

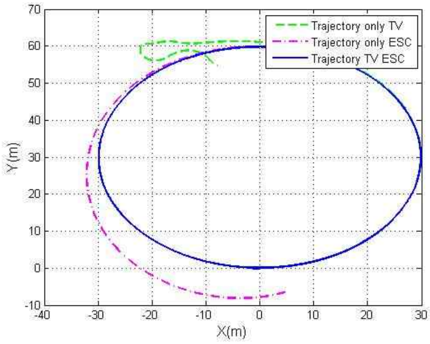
Result of circular road simulation:
Value of lateral acceleration kept between 0.6g and 0.7g by applying integrated control, and vehicle speed kept 50kph(input speed value is 60kph) to keep state of stable. Trajectory applying integrated control kept desire path.
Fig.8 is result of circular road simulation.



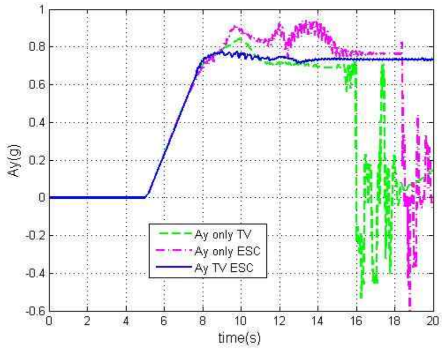
(a) Speed at circular road (0→60kph)



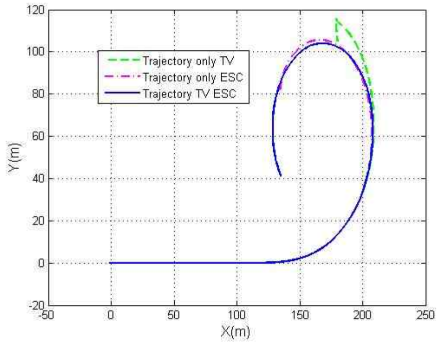
(b) Lateral acceleration at circular road (0→60kph)



(c) Trajectory at circular road (0→60kph)
Figure8: Integrated control simulation result

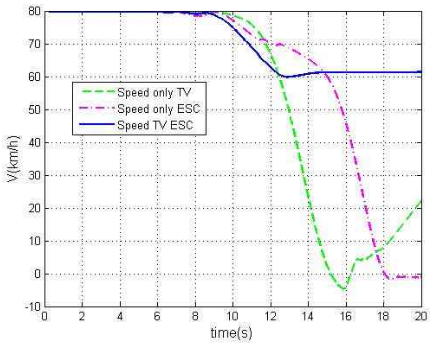


(b) Lateral acceleration at J-turn(80kph)



(c) Trajectory at J-turn (80kph)
Figure9: Integrated control simulation result

Result of J-turn simulation:
Value of lateral acceleration kept between 0.7g and 0.8g by applying integrated control, vehicle speed is not rising to 80kph(This speed is desired speed at J-turn simulation), vehicle speed kept about 60kph to keep state of stable. Trajectory kept consistently because of deceleration by integrated control. Also driving distance is increasing.
Fig.9 is result of J-turn simulation.



(a) speed at J-turn(80kph)

5 Conclusion

In wheel motor EV needs torque vectoring and ESC to improve cornering performance and durability improvement of motor, drive parts. In this paper, the torque vectoring logic and ESC logic are proposed. Also integrated control algorithm is proposed by considering operating feature of torque vectoring and ESC at various driving conditions.
The effectiveness of the proposed algorithm is verified in computer simulation using Matlab, Simulink and Carsim.
In case of applying integrated control logic, vehicle speed is limited and lateral acceleration is also limited to keep state of stable. Limited speed and lateral acceleration are expected the maximum values at each driving condition.
In the future, proposed Algorithms will be simulated by various road condition and drive condition to obtain various DB. To apply proposed integrated control logic in the real vehicle, it will be added fail safe logic and fault detection logic. Proposed algorithms and vehicle dynamic control algorithms will be applied at 4WD in wheel motor EV model.

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