Electric Differential with Fuzzy logic Controller for direct wheel drive Electric Vehicle

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Abstract. This paper presents a new approach applied to driver stability system of an electric vehicle during turns and steering maneuvers. The Direct yaw moment control is generated from the difference between the driving torques of the left and right wheel. Thus, the electric differential must be take account of the speed difference between the two wheels when cornering. To keep vehicle's stability, the fuzzy logic controller is used to generate the difference on the torques in order to control body slip angle, yaw rate to its desired values. Simulation results in Matlab/Simulink have shown that the pro-posed control scheme takes advantages of electric vehicle and enhances the vehicle stability.

Keywords: Electric vehicle, Electric differential, Fuzzy logic control, yaw moment control, Electric motor

1 Introduction

The usual configuration of electrical or non-electrical vehicles presents only one traction-motor driving two wheels, using a differential gear. For reduction of mechanical transmission components on electric vehicle, it is possible to use an electronic differential (ED) instead of the heavy mechanical differential gear for the following reasons: Firstly, an electric vehicle equipped with two individual electric motors in the rear has the advantage that can be control the traction and braking forces independently. Secondly, the electric motor torque is measurable and its generation is fast and precise[1]. With that structure, vehicle motion can be stabilized by additional yaw moment generated. In general, the DYC solution use yaw rate and vehicle sideslip body as the primary control variable [2]. Most of the existing studies have used the Ackermann and Jeantand model to solve the differential problem [3]. However, this model has the disadvantage of ignoring the influence of centrifugal force when the vehicle is driven on a curved surface and it is accurate only when the vehicle speed is very low. A yaw moment control strategy is applied to the vehicle at high speed. In this paper, a new ED control approach for a two separate wheel-motor drive EV is proposed based on the fuzzy logic control method in order to distributes the addition torque and power to each motor according to requirements. Modeling and simulation are carried out using the Matlab/Simulink tool to investigate the performance of the proposed system.

2 Overall System modeling

2.1 Vehicle model

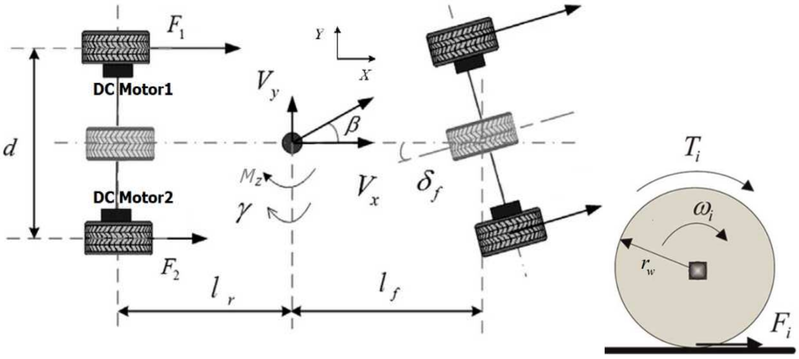


Fig. 1. Model of the rear wheel drive vehicle and applied forces [4]

Fig.1 shows the planar model of an electric vehicle with two electric motors placed at the rear wheels. This vehicle model has two degree-of-freedom (DOF), i.e., the yaw and lateral motions. However, the roll, vertical, and pitch motions are not considered here due to neglecting the suspension system. As expected, the electric vehicle is propelled only by the two rear driving wheels; we are interested in the rear traction forces f_1 andf_2. For the design of the control system, the governing equations for lateral and yaw dynamics are [5][6][7]:

$$\begin{cases} m(\dot{v}_x - v_y\gamma) = f_1 + f_2 \\ m(\dot{v}_y - v_x\gamma) = f_r(\alpha_r) + f_f(\alpha_f) \\ I_z\dot{\gamma} = l_f f_f(\alpha_f) - l_r f_r(\alpha_r) + \frac{d}{2}(f_1 - f_2) \end{cases} \tag{1}$$

For small steering and sideslip angles, we have:

$$\begin{gathered} f_f = -C_f\alpha_f; \qquad\qquad f_r = -C_r\alpha_r \\ \alpha_f = \frac{v_y + l_f\gamma}{v_x} - \delta_f; \quad \alpha_r = \frac{v_y - l_f\gamma}{v_x}; \quad \beta \simeq v_y/v_x \end{gathered} \tag{2}$$

Eqs (1) and eqs (2) yield a state-space equation as follows:

$$\begin{gathered} \dot{x} = Ax + Bu \\ y = Cx \end{gathered} \tag{3}$$

Where

$$\begin{bmatrix} \dot{\beta} \\ \dot{\gamma} \end{bmatrix} = \begin{bmatrix} -\frac{C_r + C_f}{m v_x} & \frac{C_r l_r - C_f l_f}{m {v_x}^2} - 1 \\ \frac{C_r l_r - C_f l_f}{I_z} & -\frac{C_r {l_r}^2 + C_f {l_f}^2}{I_z} \end{bmatrix} \begin{bmatrix} \beta \\ \gamma \end{bmatrix} + \begin{bmatrix} \frac{C_f}{m v_x} & 0 \\ \frac{C_f l_f}{I_z} & \frac{1}{I_z} \end{bmatrix} \begin{bmatrix} \delta_f \\ M_z \end{bmatrix} \tag{4}$$

And

$$M_z = \frac{1}{2}d(f_1 - f_2) \tag{5}$$

In the above equations, m denotes the mass of the body, $I_z$the moment of inertia concerning the yaw motion, β the side slip angle, $\dot{\gamma}$ the yaw angular acceleration, v_x the longitudinal velocity, δ_f the steering angle of front wheel, l_f, l_r the distances from the center of gravity to the front and rear axles respectively, C_f, C_r the cornering stiffness coefficients of the front and rear wheels respectively M_z the yaw moment applied by differential braking, which must be determined from the control law.

2.2 Electric motor and drives model

Furthermore, since the dynamic responses of modern motor drives are much faster than wheel dynamics, and considering the dominant poles of the closed loop sys-tem, an electric motor and its drive can be simply modeled as follows [8]:

$$\frac{T_i}{T_i^*} = \frac{k}{(1+s\tau_o)(1+s\tau_e)} \tag{6}$$

Where τ_o is the delay due to inverter and τ_e is the electrical time constant of electric motor. The tractive and braking forces transmitted from the road to tires are the products of the torques being attached to the drive wheels. Therefore we have to add two dynamic equations of rear wheels to the system (1). Each of them is commonly described by:

$$J_\omega \dot{\omega} = T_i - f_i(\lambda) r_\omega \tag{7}$$

Where J_ω, is inertia moment of the wheel; T_i is wheel torque drive of the *i*th wheel; *w* is rotary speed; *r*, is radius of the wheel; $f_i(\lambda)$ is the driving force of the *i*th wheel and depending on the slip ratio:

$$\lambda = (r_\omega \omega - v_x)/\max(r_\omega \omega, v_x) \tag{8}$$

Moreover, considering that the friction coefficient μ_i between tire and road is a function of λ_i, the driving force can be represented as:

$$f_i = \mu_i(\lambda) N_i \tag{9}$$

Where N_i normal force.

3 Controller designer

Based on the vehicle stability reference value, yaw rate is used to design the fuzzy controller to distribute the driving wheel torque. A single fuzzy controller cannot eliminate static error of the system efficiently, and its control effect of the small error is not as good as that of the PID, so it could not get high control accuracy. PID is used universally because of its high stability and easy control. But its adaptability to the nonlinearity and time variant of the control object is not satisfied. With the combina-tion of the fuzzy control and the PID control, a fuzzy PID control algorithm is used in this paper.

3.1 Reference model

In the ideal situation when the side slip angle of vehicle is zero, the desired yaw rate at the centre of gravity in the steady state relates to the steering angle with a simplified first-order transfer function [9][10]:

$$\gamma_d(s) = \frac{k_y}{(1+\tau_y s)}\,\delta_f(s) \tag{10}$$

Where k_y and τ_y are steady state gain and time constant of yaw rate response, respectively.

3.2 Fuzzy PID controller

The parameter self-tuning fuzzy-PID controller, which uses the error (e) and the error change (de) as input , adjusts the control parameter of the fuzzy-PID controller according to the value of the input to improve the performance of the controller. The basic structure of the fuzzy-PID controller is shown in Fig. 2. The controller consists of two parts , the conventional PID control section and the parameter self-tuning part based on fuzzy inference section.

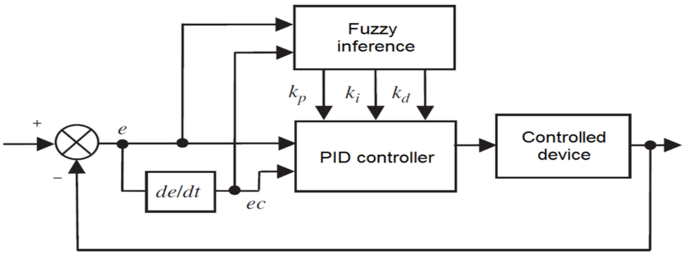


Fig. 2. The structure of Fuzzy PID controller

To improve the performance of the system, the membership function of the input e and ec use triangle function which has high sensitivity. The variable rank is 7 levels, i.e. NB (negative big), NM (negative middle), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), PB (positive big). The membership functions of E and Ec, are shown in Fig. 3 and Fig. 4 separately. The membership functions of the output variables Kp, Ki and Kd are shown in Fig.5

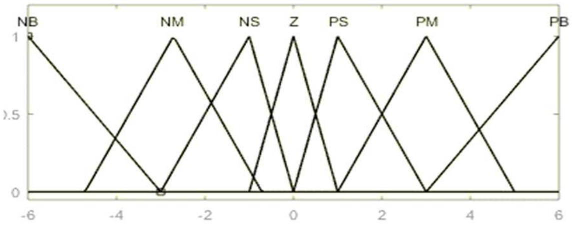


Fig. 3. The membership of (e)

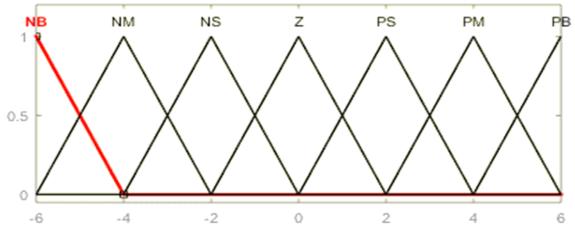


Fig. 4. The membership of (ec: change of error)

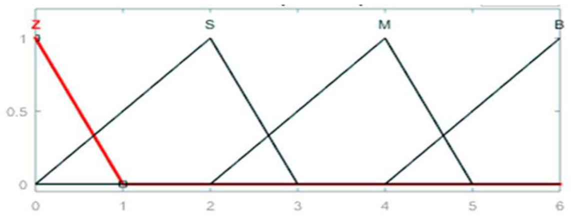


Fig. 5. The membership of output Kp,Ki and Kd

The fuzzy control rules [11] can be established, as shown in Table 1. There are 49 rules in Table 1. For example, the first rule: if e=NB and ec=NB, then Kp =B, «, =Z, Kd =S.

Table 1. Fuzzy control rule table

e	e_C						
	NB	NM	NS	ZE	PS	PM	PB
NB	BZS	BZM	BZB	BZB	BZB	ZZM	ZZS
NM	BSM	MSM	MZB	SZB	SZB	ZSM	ZSM
NS	MMZ	MBS	SMS	ZBS	SBS	SMS	SMZ
ZE	MBZ	SBZ	ZBS	ZBZ	ZBS	SBZ	NBZ
PS	SMZ	SBS	SMS	ZBS	SBS	MMS	MMZ
PM	SSM	ZSM	SZB	SZB	MZB	MSM	BSM
PB	ZZS	ZZM	BZB	BZB	BZB	BZM	BZS

3.3 Electric differential design

When the steering angle does not equal to zero or the adhesion coefficients between the driven wheels and ground are not the same, the vehicle will make a tum. Under these conditions, the outer wheels must run faster than the inner ones in order to maintain vehicle stability and reduce the tire abrasion. The torque distribution law has the role as an electric differential than The control input M_z,, obtained by controller is distributed to two motors based on the following equations:

$$\begin{cases} M_z = \frac{1}{2} d({f_1}^* + {f_2}^*) \\ T_{acc} = r_w({f_1}^* + {f_2}^*) \end{cases} \tag{11}$$

d is the half distance between left and right wheels. By solving the simultaneous equation (11), the force command signals to left and right wheels (${f_1}^*; {f_2}^*$) can be determined from M_z, and accelerator command T_{acc}. Thus, the torque commands to two in-wheel motors can be calculated as [3]:

$$\begin{cases} {T_1}^* = r_w {f_1}^* \\ {T_2}^* = r_w {f_2}^* \end{cases} \tag{12}$$

Using eq (12) into eq(11), we can obtain:

$$\begin{cases} {T_1}^* = \frac{d}{2r_w}(M_z - T_{acc}) \\ {T_2}^* = \frac{d}{2r_w}(M_z + T_{acc}) \end{cases} \tag{13}$$

Finally, by Matlab/Simulink, the simulation model of the ED system based on the fuzzy PID controller, as shown in Fig. 6 and Fig 7.

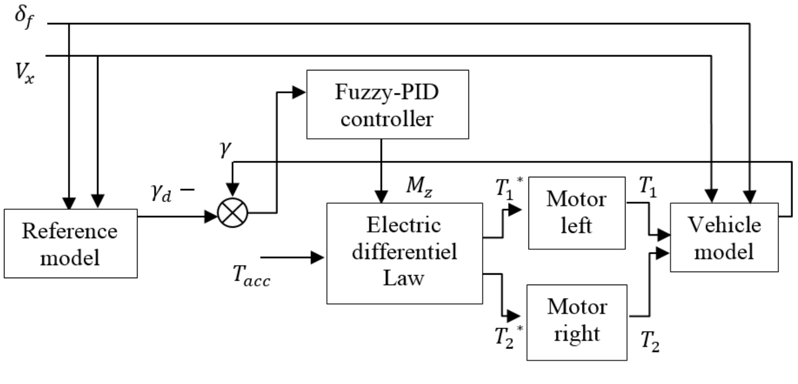


Fig. 6. The structure of control system

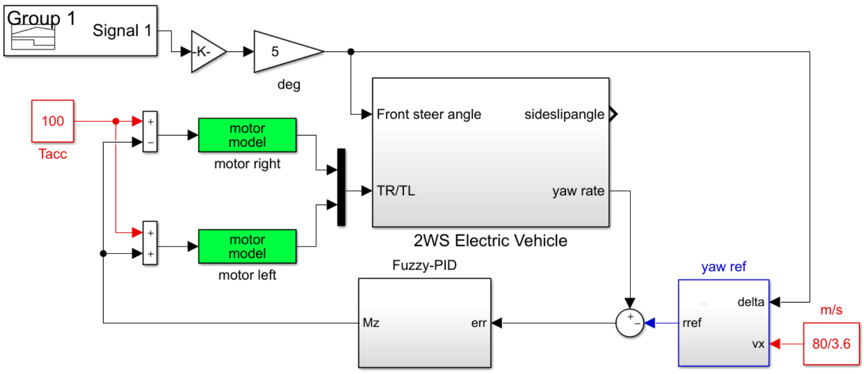


Fig. 7. Block diagram of overall system in Simulink.

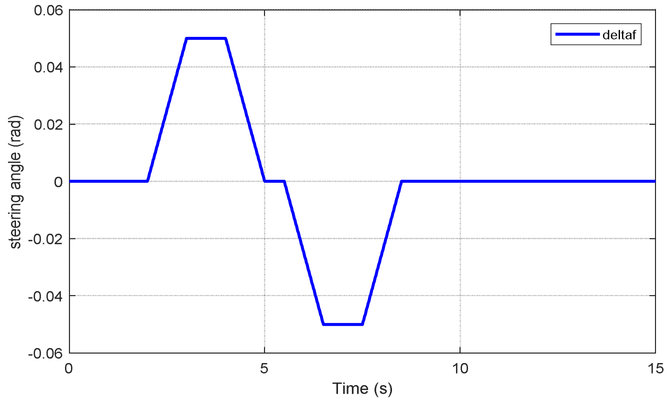
3.4 Results and discussion

In order to verify the effectiveness of proposed ED system algorithm, two steering wheel maneuvers change on the right and the left, are investigated by Matlab/Simulink simulation. Vehicle parameters for simulation and electric drive (DC motor) parameters for simulation are shown in Table 2. The simulation results are obtained for a severe cornering maneuver. The vehicle speed is 80 km/h. The steering angle input is shown in Fig.8(a). The simulation results of Fig.8 (b) indicate for the fuzzy PID controlled, the yaw rate response can follow the desired response. Fig8(c) shows the yaw moment control input changing between[-4000,4000 Nm].

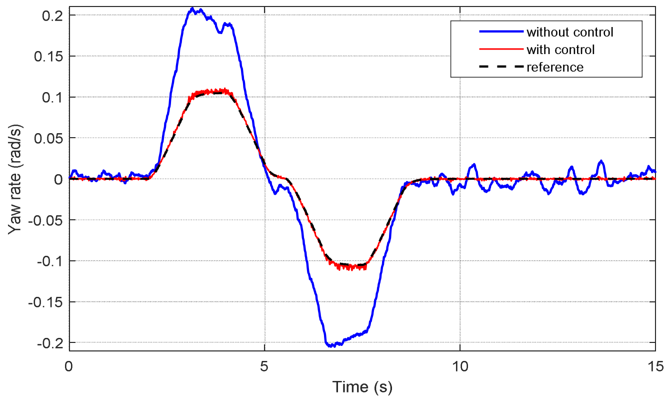
The rear torque motor and motor speed shows in Fig.8(d) and 8(e) proved a good control of the electric vehicle on the steering maneuver and electric vehicle can follow the desired trajectory on safety fig8.(f).

Table 2. Parameters of vehicle and motor’s drive.

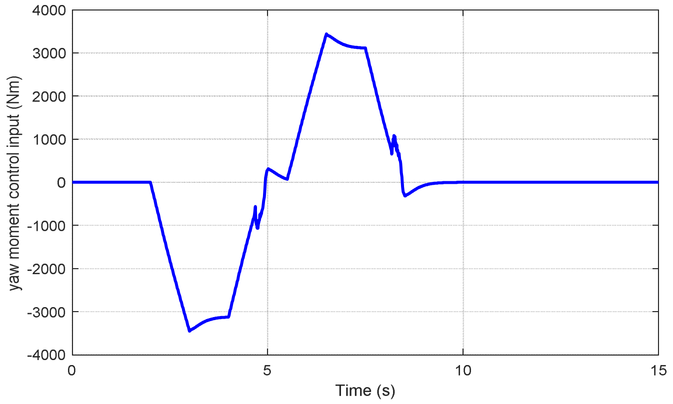
Vehicle Parameters	Design	Motor Parameters	Design
m = 1980	Vehicle mass	R=0.1 Ω	Resistance
iz = 3758	Vehicle yaw moment of inertia	L=0.01 H	inductance
lf = 1.358	Distance from CG to front axle	K=0.01	EMF constant
lr = 1.472	Distance from CG to rear axle	J=0.8	Wheel inertia.
cf = 41000	Front tire cornering stiffness	Gr=1:10	Gear box ratio
cr = 74000	Rear tire cornering stiffness		
v = 80/3.6	Vehicle speed		
d = 1.7	Vehicle wide		



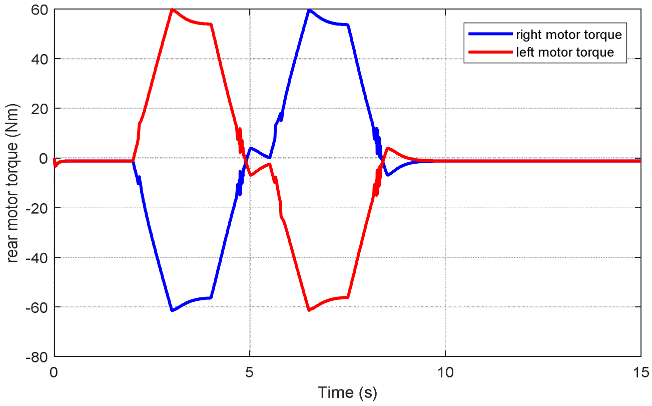
(a) Steering angle



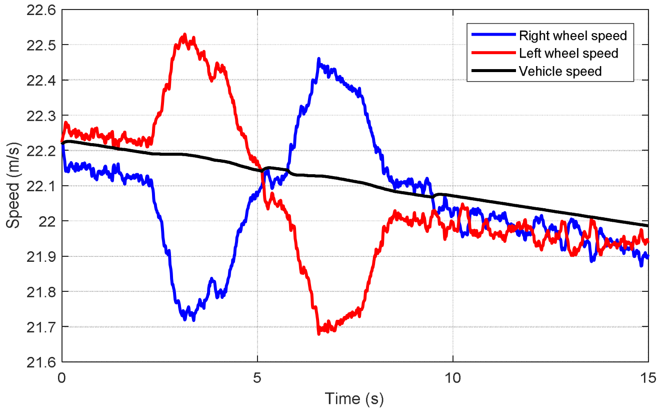
(b) Yaw rate



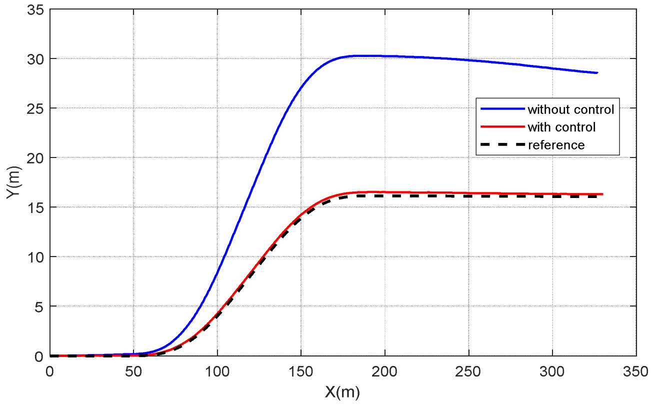
(c) Yaw moment control input



(d) Rear Motors torque



(e) Vehicle and wheel drive speed



(f) Trajectories of Electric vehicle.

Fig. 8. Vehicle response under steering manoeuvre at 80 Km/h.

CONCLUSION

The motor-drive EVs is considered as the best choice in terms of yaw stability control in different driving conditions. If the wheel motor is capable of generating both tractive and braking torques, the associated Electric differential EDs can provide more yaw moment to assist the driver to negotiate the turn, especially at low speed corning manoeuvres. The simulation results show better performances ensured by the yaw moment control. As a result, it can be concluded that the vehicle handling stability is greatly improved using proposed controller.

In the next work, the further research and effort can be devoted that the real-time knowledge of vehicle parameters and states is indispensable for control of EVs. However, some parameters and states can be directly measured by sensors, some others have to be estimated due to costs or other practical issues. For this purpose, we will introduce some devices and estimation methodologies like observer for vehicle parameter and state acquisition for the best control of EV under critical driving situations.

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