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Stability control of electric vehicles with in-wheel motors by considering tire slip energy

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A B S T R A C T

Tire wear and overuse are serious issues for four-in-wheel-motor-driven electric vehicles (FIWMD EVs). As a result, this paper proposes a hierarchical control framework to improve the safety of FIWMD EVs while save the tire slip energy (i.e. reduce the tire wear), which includes a linear quadratic regulator (LQR) in the outer layer and a holistic corner controller (HCC) in the inner layer. The LQR can highly improve the lateral stability of the vehicles under extreme conditions by producing an additional yaw moment and a front wheel steering angle. Whereas, the HCC can efficiently distribute the deviation of the longitudinal force and the additional yaw moment by a step-ahead prediction. In this framework, to reduce the tire slip energy, a semi-empirical tire slip energy model is developed and used for tuning the HCC controller. In this way, not only the lateral stability of such EVs can be ensured but also the tire slip energy can be reduced. More importantly, this paper compares the lateral stability and slip energy of the vehicle under lane change condition between four methods – without control, traditional axis distribution, tire workload usage and tire slip energy. The results demonstrate that the proposed controller presents an excellent control capability. In addition, different from the widely used axis load distribution, the longitudinal velocity of the proposed method is more stable. More importantly, the tire slip power and energy are much smaller than others. It achieves 16.62% reduction of the tire slip energy.

1. Introduction

As a solution to environmental and energy problems, electric vehicles (EVs) have drawn more and more attention because of its features such as the low or zero emission and high efficiency [1–3]. One highlighted advantages of FIWMD EVs also render more academic researcher caused by control flexibility [4], which can also further improve the stability if the torque of drive motors is properly distributed [5]. In contrast, the tire wear probably appears because of the unreasonable distribution of tire forces. Hence, this paper aims to the torque distribution of four-in-wheel-motor-driven electric vehicles and active front steering (FIWMD + AFS-EVs).

With five independently controllable tire forces for vehicle plane motion control, i.e. four longitudinal forces by in-wheel motors and one lateral force by active front steering (AFS), only three constraints i.e. vehicle longitudinal, lateral, and yaw

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Nomenclature

m	vehicle body mass
I_z	moment of vehicle body inertia about Z
l_f	distance from CG to front axis
l_r	distance from CG to rear axis
c_f	front actual cornering stiffness
c_{fo}	front nominal cornering stiffness
c_{ro}	rear nominal cornering stiffness
t_{wf}	distance of front wheel base
t_{wr}	distance of rear wheel base
g	gravity acceleration
h_g	height of CG
F_z	the vertical load of the tire
ω_i	angular velocity of wheel rotation
$\Delta M_{z,cg}$	additional yaw moment
$\boldsymbol{E}$	the error of CG force
β	sideslip angle of CG
a_x	longitudinal acceleration of CG
a_y	lateral acceleration of CG
r	vehicle yaw rate
$\boldsymbol{E}'$	the deviation of CG force considering step-ahead prediction
V_x	vehicle longitudinal velocity
β_d	desired sideslip angle
r_d	desired yaw rate
$\boldsymbol{E}_s$	current deviation of CG longitudinal force and yaw moment
F_{x1}	axis distribution longitudinal force at front left wheel
$\boldsymbol{W}_E$	CG force error weight matrix
$\boldsymbol{W}_c$	control error weight matrix
R_{eff}	effective tire rolling radius
T_{di}	extern torque applied at wheel
$\Delta\delta_f$	additional front wheel steering angle
δ_f	front wheel steering angle
ΔM_z	additional yaw moment
f_{x1}	longitudinal force of front left wheel
Δf_{x1}	incremental force of front left wheel
$F^*_{x,cg}$	desired CG longitudinal force
$F^*_{y,cg}$	desired CG lateral force
$M^*_{z,cg}$	desired CG yaw moment
$F_{xa,cg}$	actual longitudinal CG force
$F_{ya,cg}$	actual lateral CG force
$M_{za,cg}$	actual yaw moment
$\Delta F_{x,cg}$	additional longitudinal CG force
$\Delta F_{y,cg}$	additional lateral CG force
ΔT_{di}	additional extern driven torque
$\boldsymbol{Q}$	positive definite matrix
$\boldsymbol{R}$	positive definite matrix
S_x	the longitudinal slip ratio
S_y	the lateral slip ratio
V_{sx}	the longitudinal slip velocity between road and tire
V_{sy}	the lateral slip velocity between road and tire
F_{sx}	the longitudinal slip force of the wheel on the center of ground contact patch
F_{sy}	the lateral slip force of the wheel on the center of ground contact patch
P_{sx}	the longitudinal slip power
μ	road friction coefficient
AFS	active front steering
DYC	directed yaw-moment control
FIMWD EVs	four-in-wheel-motor-driven electric vehicles Electric Vehicles
EVs	electric vehicles