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Enhancing vehicle cornering limit through sideslip and yaw rate control

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ABSTRACT

Fully electric vehicles with individually controlled drivetrains can provide a high degree of drivability and vehicle safety, all while increasing the cornering limit and the 'fun-to-drive' aspect. This paper investigates a new approach on how sideslip control can be integrated into a continuously active yaw rate controller to extend the limit of stable vehicle cornering and to allow sustained high values of sideslip angle. The controllability-related limitations of integrated yaw rate and sideslip control, together with its potential benefits, are discussed through the tools of multi-variable feedback control theory and non-linear phase-plane analysis. Two examples of integrated yaw rate and sideslip control systems are presented and their effectiveness is experimentally evaluated and demonstrated on a four-wheel-drive fully electric vehicle prototype. Results show that the integrated control system allows safe operation at the vehicle cornering limit at a specified sideslip angle independent of the tire-road friction conditions.

1. Introduction

Fully electric vehicles with individually controlled electric motor drives provide significant benefits in terms of vehicle cornering response. In particular, the control of the left-to-right and front-to-rear wheel torque distributions, also called torque-vectoring or direct yaw moment control, has been shown to be beneficial in: i) shaping the understeer characteristic (i.e., the graph of steering wheel angle against lateral acceleration) [1,2] in quasi-static conditions (i.e., when driver inputs are slowly changing), including non-zero longitudinal accelerations; and ii) enhancing the transient cornering response through the reduction of the delays between steering wheel angle and yaw rate, the decrease of the yaw rate and sideslip overshoots, and the increase of the yaw rate damping [1]. With respect to ii), the precise controllability of the individual wheel torques, together with the higher bandwidth typical of electric motor drives and their capability of generating both positive and negative torques, allows better dynamic performance in comparison with conventional stability control systems based on the actuation of the friction brakes [3,4].

Several controllers have been proposed for the direct yaw moment control of fully electric vehicles with multiple motors, such as proportional integral derivative (PID) controllers running in parallel with non-linear feedforward contributions [1], linear quadratic regulators [5,6], and various configurations of sliding mode control [7,8], each of them with specific

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Nomenclature

Subscripts

'LF'	left front wheel
'RF'	right front wheel
'LR'	left rear wheel
'RR'	right rear wheel
'F'	front axle
'R'	rear axle
'k'	a generic discrete parameter

Symbols

a, b	front and rear semi-wheelbases
a_x	longitudinal acceleration
a_y	lateral acceleration
$a_{y,max}$	maximum reference value of lateral acceleration
A_k, B_k, $\overline{D}_{x,k}$ and W	process equation matrices in the extended Kalman filter
c	stiffness parameter of the brush-type model of the tires
D_a	damping ratio of the actuators
e	error vector
e_r	yaw rate error
e_β	sideslip angle error
e_1, e_2, E	first output singular vector, second output singular vector, singular vector matrix within the singular value decomposition of the sensitivity function
F_x	longitudinal tire force
F_y	lateral tire force
F_z	vertical tire force
$F_{z,STATIC}$	static vertical load
G_a	plant transfer function
G_{M_z}	transfer function (with components $G_{M_z,r}$ and $G_{M_z,\beta}$) from the actual yaw moment to vehicle states
G_p	transfer function (with components $G_{p,r}$ and $G_{p,\beta}$) from the reference yaw moment to vehicle states
G_s	transfer function of the shaped plant
G_δ	transfer function (with components $G_{\delta,r}$ and $G_{\delta,\beta}$) from steering angle to vehicle states
H_k, D_k, $\overline{D}_{z,k}$ and Z	measurement equation matrices of the extended Kalman filter
H_{RC}	roll center height
H_{ROLL}	vertical distance between center of gravity and roll center
I	identity matrix
j	imaginary unit
J_z	yaw mass moment of inertia
l_p	half-length of tire contact patch
k_{ramp}	slope for the increase of the reference yaw rate after the de-activation of the sideslip controller
k_{ROLL}	suspension roll stiffness
K	control system matrix
K_{corr}	parameter of the yaw rate correction algorithm
K_p	proportional gain
K_r	yaw rate controller
K_s	H_∞ optimal controller
K_β	sideslip angle controller
K_∞	final controller formulation
L	vehicle wheelbase
m	vehicle mass
M_z	reference control yaw moment
$M_{z,actual}$	actual yaw moment applied to the vehicle
$M_{z,r}$	yaw moment contribution related to yaw rate control
$M_{z,r,FB}$	feedback part of $M_{z,r}$
$M_{z,r,FF}$	feedforward part of $M_{z,r}$
$M_{z,\beta}$	yaw moment contribution related to sideslip control
$M_{z,\beta,lim}$	threshold of $M_{z,\beta}$ for activating the reference yaw rate ramp
N_r, N_β, N_δ	stability derivatives in the yaw moment balance equation
r, $\dot{r}$	yaw rate, yaw acceleration
r_{LUT}	yaw rate output from the look-up table
r_{ref}	reference yaw rate
ref	reference vector
r_1, r_2, R	worst reference direction, best reference direction, matrix with the worst and best reference directions according to the singular value decomposition
s	Laplace operator or abbreviation for second
S	closed-loop sensitivity function
SR	slip ratio
t	time
T	track width
T_i	integral parameter
T_I, T_O	input and output complementary sensitivity functions
u	plant input
u_1, u_2, U	first output singular vector, second output singular vector, singular vector matrix within the plant singular value decomposition
v	vehicle speed
V^H	input singular vector of the plant
W_1, W_2	pre- and post- compensators
w_k and v_k	extended Kalman filter process and measurement noises
w_β	weighting factor for sideslip estimation
x	state vector
Y_r, Y_β, Y_δ	stability derivatives in the lateral force balance equation
z	output vector
α, α_{sl}	slip angle and sliding limit slip angle
β, $\dot{\beta}$	sideslip angle, sideslip rate
$\hat{\beta}$	estimated sideslip angle
$\hat{\beta}_{EKF}$	sideslip angle estimated by the extended Kalman filter
β_{eq},$\dot{\beta}_{eq}$	values of sideslip angle and sideslip rate at the equilibrium for the passive vehicle
$\beta_{eq,Sport}$, $\dot{\beta}_{eq,Sport}$	values of sideslip angle and sideslip rate at the equilibrium for the controlled vehicle in Sport Mode