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ORIGINAL ARTICLE

Lateral motion control of skid steering vehicles using full drive-by-wire system

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Abstract This paper introduces a control system to stabilize the motion of skid steering vehicles, extends their stability limit and makes their handling performance similar to that of the conventional two-wheel steering vehicle. For this purpose, the yaw rate response of the two degree of freedom (2DOF) linear model of the conventional two-wheel steering vehicle is chosen as a model response. The model following control theory is used to introduce the direct yaw moment needed to stabilize and steer the skid steering vehicle. The direct yaw moment has been split into the four tires based on two methods. The first method is based on a simple distribution technique (SD), whereas the second method is based on an independent distribution technique (ID) where the four wheels can be driven individually using a full drive-by-wire system. A comprehensive nonlinear dynamic model of the skid steering vehicle has been simulated using Matlab/Simulink in order to examine the effectiveness of the proposed control system. The results of both open and closed loop tests show that the proposed control system has a significant effect on stabilizing the lateral motion of skid steering vehicles as well as improving their handling characteristics.

1. Introduction

Over the past decade, a few researches have addressed the increase in the stability limit of conventional two-wheel steering vehicles based on an optimal distribution of both longitudinal and lateral tire forces. Suzuki et al. [1] studied feed-forward types of tire force distribution controls for full drive-by-wire electric vehicles based on two strategies. The first strategy was to minimize the tire workload whereas the second strategy was to minimize the tire energy dissipation. The effect of the control system was investigated experimentally on a proving ground where it was concluded that the first strategy has a great influence on the vehicle stability. Goodarzi and Mohammadi [2] designed an integrated control of three layers for improving the stability and the fuel economy of a 4-wheel-drive hybrid vehicle. One of the three layers was to determine the optimum values of longitudinal and lateral forces of the four tires that allow achieving a desired vehicle response.

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Nomenclature

a	distance from the mass center of the vehicle to front axle
a_x	longitudinal acceleration
a_{xdes}	traction/braking command from the driver
a_y	lateral acceleration
A	stability factor
b	distance from the mass center of the vehicle to rear axle
B_{pitch}	suspension pitch damping coefficient
B_{roll}	suspension roll damping coefficient
C_f	cornering stiffness of front wheel
C_r	cornering stiffness of rear wheel
dr	distribution ratio of the direct yaw moment
F_{xi}	friction force in the longitudinal direction of wheel i (i = 1–4)
F^*_{xi}	required longitudinal force at wheel i (i = 1–4)
F_{yf}	linear lateral force produced by front wheels
F^*_{yf}	estimated lateral force produced by front wheels
F_{yi}	friction force in the lateral direction of wheel i (i = 1–4)
F_{yr}	linear lateral force produced by rear wheels
F^*_{yr}	estimated lateral force produced by rear wheels
F_{zi}	estimated vertical load of wheel i (i = 1–4)
g	gravity acceleration
G_R	yaw rate gain
h_s	sprung mass height
I_x	mass moment of inertia about the x-axis
I_y	mass moment of inertia about the y-axis
I_z	yaw moment of inertia
J_i	moment of inertia of wheel i (i = 1–4)
k	time constant
k_f	lateral weight-shift distribution on the front wheel
k_r	lateral weight-shift distribution on the rear wheel
K_{pitch}	suspension pitch stiffness
K_{roll}	suspension pitch stiffness
M_z	direct yaw moment control
M_{zf}	direct yaw moment to be generated from front wheels
M_{zr}	direct yaw moment to be generated from rear wheels
p	pitch angular velocity of the vehicle about the y-axis
$\dot{p}$	pitch angular acceleration of the vehicle about the y-axis
q	roll angular velocity of the vehicle about the x-axis
$\dot{q}$	roll angular acceleration of the vehicle about the x-axis
r	steering gear ratio
R	wheel radius
s	Laplace transform
S	sliding surface
t	vehicle tread
T_i	traction/braking torque at wheel i (i = 1–4)
V	speed of the vehicle
V_x	speed of the vehicle in the longitudinal direction
$\dot{V}_x$	acceleration of the vehicle in the longitudinal direction
V_y	speed of the vehicle in the lateral direction
$\dot{V}_y$	acceleration of the vehicle in the lateral direction
W	vehicle weight
W_s	vehicle sprung weight
x	vehicle longitudinal direction
y	vehicle lateral direction
z	vehicle vertical direction
α	sideslip angle of the vehicle
α_{es}	estimated vehicle sideslip angle
$\dot{\alpha}$	time derivative of sideslip angle
γ	yaw rate of the vehicle
γ_{ss}	steady state yaw rate response
$\dot{\gamma}$	yaw acceleration of the vehicle
ζ	damping factor
θ	pitch angle of the vehicle
μ	sum of squared normalized longitudinal forces produced at the four wheels
φ	roll angle of the vehicle
ψ	driver's steering wheel angle
ω_i	angular velocity of wheel i
ω_n	natural frequency

The simulation results showed noticeable improvements on the stability and fuel consumption of the vehicle. Following the driver command, Wang et al. [3] found the optimum tire forces to follow a given target path. Computer simulations were conducted to validate the effectiveness of the proposed control. In the simulation, a 7 degrees of freedom vehicle model was used while the magic formula model was used to detect the tire forces. Based on proportional, integral and derivative (PID) control theory, Kim et al. [4] determined the yaw moment required to stabilize the lateral vehicle motion of rear wheel drive electric vehicles. Then, they distributed the yaw moment to the wheels in order to calculate the needed longitudinal tire force by taking into account the desired longitudinal force according to the driver input through the accelerator pedal. CarSim software was used to verify the effectiveness of the proposed method. During cornering with high speed, the simulation results showed a saving in the electric energy in addition to an improvement of the vehicle stability. Naraghi et al. [5] presented an integration of the vehicle longitudinal and lateral motion control in which the tire forces were distributed based on an adaptive optimal approach. In the proposed system, each tire was assumed to be steered and driven and/or braked individually. Digital simulations were executed based on a comprehensive nonlinear vehicle model. The results proved the positive influence of the proposed control. Mokhiamar [6] and Mokhiamar and Abe [7] proposed an optimum distribution of lateral and longitudinal tire forces based on minimizing the tire workload. The 2DOF state variables, yaw rate and sideslip angle, were chosen as desired responses for the model following control. A comprehensive nonlinear vehicle model was used to predict the dynamics of the controlled vehicle via computer simulations. The results