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Model predictive control-based efficient energy recovery control strategy for regenerative braking system of hybrid electric bus

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ABSTRACT

As one of the main working modes, the energy recovered with regenerative braking system provides an effective approach so as to greatly improve fuel economy of hybrid electric bus. However, it is still a challenging issue to ensure braking stability while maximizing braking energy recovery. To solve this problem, an efficient energy recovery control strategy is proposed based on the modified nonlinear model predictive control method. Firstly, combined with the characteristics of the compound braking process of single-shaft parallel hybrid electric bus, a 7 degrees of freedom model of the vehicle longitudinal dynamics is built. Secondly, considering nonlinear characteristic of the vehicle model and the efficiency of regenerative braking system, the particle swarm optimization algorithm within the modified nonlinear model predictive control is adopted to optimize the torque distribution between regenerative braking system and pneumatic braking system at the wheels. So as to reduce the computational time of modified nonlinear model predictive control, a nearest point method is employed during the braking process. Finally, the simulation and hardware-in-loop test are carried out on road conditions with different tire–road adhesion coefficients, and the proposed control strategy is verified by comparing it with the conventional control method employed in the baseline vehicle controller. The simulation and hardware-in-loop test results show that the proposed strategy can ensure vehicle safety during emergency braking situation and improve the recovery energy almost 17% compared with the conventional rule-based strategy in the general braking situation. Therefore, the proposed control strategy might offer a theoretical reference for the design of the actual braking controller in engineering practice.

1. Introduction

The energy depletion and environment pollution have always been the problems hindering the rapid development of the automotive industry. Hybrid electric vehicle (HEV) technology might be the primary solution, due to its characteristics of better fuel economy and lower exhaust emissions in comparison to conventional vehicles [1]. Within the fast expansion of HEV technology, its application to the area of urban buses has made great progress [2]. Among various configurations of HEV, single-shaft parallel powertrain with the automatic mechanical transmission (AMT) have attracted more and more attention due to its compact structure and transmission efficiency [3]. Braking energy recovery is an important working mode for improving fuel consumption and reduce pollutant emissions in HEV. A research about the potential of this technique shows that from one third to one half of the driving energy is dissipated during braking in urban driving circles [4]. Regenerative braking control strategies included series and parallel types. In the Parallel strategy, the friction braking system is the same as in conventional vehicles, and the regenerative torque is added into the friction braking system proportionately. In the series strategy, the friction braking torque can be modulated, and the overall braking torque is controlled to meet the driver demand.

In order to get more efficiency and better capacity of the regenerative braking energy, the existing research has focused on the series strategy. Using this configuration, the regenerated energy is mainly limited by three constrains [5]. First, the regenerative torque depends on the maximum braking torque provided by the motor, which is designed for high torque and power density [6]. Second, the regenerative power is limited by the charging power capability of the battery [7]. To avoid the over-charging or over-discharging and provide a powerful guarantee for the optimization of HEV, the battery's power characteristic should be considered in

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Nomenclature

A	vehicle frontal area (m^2)
a_1	acceleration of vehicle (m/s^2)
b	longitudinal distance from rear wheel to the center of gravity of vehicle (m)
C_D	aerodynamic drag coefficient (–)
e_i	difference of the desired vehicle speed and the predictive vehicle speed (m/s)
$\tilde{e}$	difference of v_{mod} and v_{act} (m/s)
F_{resist}	total resist force (N)
F_w	wind resist force (N)
F_{z1}, F_{z2}	perpendicular force of the front and rear wheels respectively (N)
h_c	control horizon (–)
h_p	prediction horizon (–)
$\tilde{i}$	corresponding output of the set W and W_v (–)
J_1, J_2	moments of inertia of the front, rear wheels respectively ($kg\ m^2$)
K_{b1}, K_{b2}	stiffness for the front wheel and rear wheel respectively (kN/m)
k_{pb}	the ratio coefficient between the pneumatic braking torque and the braking pressure (–)
m	overall mass of vehicle (kg)
m_s	sprung mass of vehicle (kg)
p	pneumatic pressure in the braking chamber (MPa)
p_{ij}	optimal position of the particle in its history (–)
R_1, R_2	radius of the vehicle wheel (m)
r	variation factor (–)
s_i	slip ratio of the wheels (–)
T_{b1}, T_{b2}	pneumatic braking torque on the front and rear wheel (N m)
$T_{pchange,\max}$	maximum braking torque change rate of the pneumatic braking system (N m)
$T_{rechange,\max}$	maximum braking torque change rate of the motor (N m)
Ts	sample time adopted in the model prediction (s)
u_{cont}	output of the controller (–)
u_{hold}	change rate in the pressure hold phase (MPa/s)
$u_{ij}(t+1)$	position of the particle in new generation (–)
u_x	change rate of braking pressure (MPa/s)
v	vehicle speed (m/s)
v_{mod}	modified vehicle speed using the feedback method (m/s)
v_{pre}	vehicle speed based on the predictive model (m/s)
W	a compact subset of the domain of the controller inputs (–)
w_a, w_b, w_c	weight factor for the inertia velocity, velocity to go to the optimal value of the particle in the history, velocity to go to the optimal combination respectively (–)
$\tilde{w}$	factors in W_v (–)
X	current vehicle states (–)
Z	vertical motion of vehicle (m)
α_1, α_2	angular acceleration of the front and rear wheel (rad/s^2)
μ_i	friction coefficient (–)
η_i	efficiency of the set of wheel to battery (–)
ω_m	angular velocity of the motor axle (r/min)
τ_0	lag time of the pneumatic braking system (s)
τ_p	time lag coefficient (–)

a	longitudinal distance from the front wheel to the center of the gravity of vehicle (m)
B,C,D,E	coefficients of the magic formula (–)
C_1, C_2	damping coefficients of the front suspension and the rear suspension respectively (kN s/m)
D_0	vertical distance between the center of the gravity of vehicle to the pitching axle (m)
$\bar{e}$	difference of v_{pre} and v_{act} (m/s)
F_f	roll resist force (N)
F_{s1}, F_{s2}	forces of the suspension on the front wheel and rear wheel (N)
F_{x1}, F_{x2}	the braking force provided by the ground on the front and rear wheels (N)
f_1, f_2	coefficient of roll resist force (–)
h_i	weight factor of the difference in i time step (–)
I_c	battery charging current (A)
J	cost function (–)
J_y	the moment of inertia of the vehicle in the OY direction ($kg\ m^2$)
K_1, K_2	stiffness of the front suspension and rear suspension respectively (kN/m)
l	longitudinal distance from the front wheel to rear wheel (m)
m_1, m_2	mass of the front wheel and rear wheel respectively (kg)
$P_{batt\_\lim}$	maximum charging power of battery (W)
p_{gi}	position in the optimal combination (–)
p_t	target braking pressure (MPa)
R_{int}	Initial resistance of battery (Ω)
S_{xrefer}	desired slip ratio (–)
T_b	pneumatic braking torque (N m)
T_{change}	change rate limits for the particle (N m)
T_{reb}	regenerative braking torque (N m)
$Tb_{re,\max}$	maximum braking torque the motor can provide (N m)
U_c	battery charging voltage (V)
u_{dec}	change rate of the braking pressure reduction (MPa/s)
$u_{ij}(t)$	position of the particle in previous generation (–)
$u_{Inc.}$	change rate when the braking pressure increasing (MPa/s)
V_{oc}	the battery open-circuit voltage (V)
v_{act}	actual vehicle speed (m/s)
v_{ij}	velocity of particle (–)
v_{ref}	desired vehicle speed (m/s)
W_v	a set of finite point which is the set, W (–)
w_x, w_y, w_z	weight factors that denote the important level of the vehicle speed tracking performance, the braking energy recovery efficiency, the vehicle safety performance respectively (–)
$\tilde{w}^{NP}$	the nearest point (–)
x	longitudinal motion of vehicle (m)
Z_1, Z_2	vertical motions of the front wheel and rear wheel respectively (m)
θ	roll angle of sprung mass (°)
η_{motor}	motor efficiency (–)
η_{trans}	transition system efficiency (–)
ω_i	rotation speed of the wheel (rad/s)
τ_x	time taken to reach the target braking pressure (s)
σ	tire–road friction adhesion coefficient (–)

the control strategy [8]. Third, the braking torque is eventually limited by available tire–road friction. Hence, the available regenerative braking torque might not be always large enough to satisfy the braking demand. Consequently, the general braking system of hybrid electric bus (HEB) is composed of both electric regenerative braking system (RBS) and pneumatic friction braking system. During the braking maneuver, the braking torque would be distributed between regenerative braking torque, provided by motor at the rear wheels, and the friction braking torque at the front and rear wheels provided by pneumatic braking system. Considering highly