Mechanical Systems and Signal Processing 109 (2018) 196–219

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Braking sense consistency strategy of electro-hydraulic composite braking system

Chunyan Wang, Wanzhong Zhao *, Wenkui Li

College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

ARTICLE INFO

Article history:
Received 5 December 2017
Received in revised form 2 February 2018
Accepted 25 February 2018

Keywords:
Electro-hydraulic composite braking
Braking sense
Consistency
Multi-objective optimization
Compensation control

ABSTRACT

For the electro-hydraulic composite braking system, the regenerative braking is characterized by quick response, while the response of hydraulic braking is hysteretic. As the braking mode is switched, it always has a mutation of the braking torque and causes the driver to produce inconsistent braking sense. This paper mainly discusses the braking sense consistency strategy from two aspects of multi-objective optimization and compensation control. An optimized allocation method of braking force is explored under multi objectives and multi constraint conditions, which is to find the optimal distribution ratios of front and rear axles, as well as regenerative braking and hydraulic braking. Based on this, the braking sense consistency controller is further designed to make up the difference of braking force and keep the braking force change rate unchanged. Simulation results show that the composite braking system with the proposed strategy can not only eliminate the fluctuation in braking mode switching and ensure the driver obtaining consistent braking sense, but also has satisfactory tracking performance and strong anti-interference ability.

1. Introduction

Vehicles always start and brake more frequently in urban conditions, thus the energy dissipated to the air in the process of vehicle braking takes up about half of the total driving energy [1]. However, the traditional mechanical braking has consumed this part of energy in the form of thermal losses, which results in a large amount of energy waste. Compared with the traditional braking, the electro-hydraulic composite braking can conduct both hydraulic braking and regenerative braking according to different working conditions of the vehicle. Regenerative braking, also known as braking energy recovery, can convert a part of the vehicle's mechanical energy into electrical energy and store it in a storage device. When the car starts or accelerates again, the reclaimed braking energy can be converted to the kinetic energy required for the vehicle. Thus it is able to improve the energy efficiency effectively [2–4]. Research shows that under urban conditions of frequent braking, the regenerative braking system can recover 30–60% of the total braking energy and make the mileage extend 10–30% [5].

Nowadays, researches about the electro-hydraulic composite braking mainly focuses on two aspects: one is the distribution strategy of the braking force, and the other is the control strategy of braking system. For the first aspect, the braking force distribution strategy is to determine the distribution ratio of the regenerative power and the hydraulic power, and the distribution ratio of the front and rear axles. The former directly affects the energy recovery of braking system, and the latter is closely related to the braking stability. Lian et al. studied the linearization of the safe braking range on the

---

* Corresponding author.
E-mail address: zwz@nuaa.edu.cn (W. Zhao).

https://doi.org/10.1016/j.ymssp.2018.02.047
0888-3270/

Nomenclature

δ	front wheel angle, rad
Vx	longitudinal speed, m/s
Vy	lateral speed, m/s
β	sideslip angle, rad
r	yaw rate, rad/s
F_{xi}	longitudinal force of tire, N
F_{yi}	lateral force of tire, N
m	mass of the vehicle, kg
a	distance from the front axle to the center of mass, m
b	distance from the rear axle to the center of mass, m
t_{w1}	wheel base of the front axle, m
t_{w2}	wheel base of the rear axle, m
I_z	moment of inertia around the Z axis, kg·m^2
I_{tw}	wheel's moment of inertia, kg·m^2
ω	wheel's angular velocity, rad/s
R_w	wheel's radiu, m
T_{bi}	braking moment, N·m
T_{fi}	rolling resistance moment, N·m
u	amplifier output voltage, V
r_m	resistance of the coil, Ω
i	current through the coil, A
L	inductance of the coil, H
p	outlet pressure of the relief valve, MPa
A_s	area of the end face of the valve core, m^2
k_i	current-force gain coefficient of proportional electromagnet
x_v	armature shift, m
m_s	spool mass, kg
B_s	spool damping, N/(m/s)
K_s	rigidity of the valve core spring, N/m
Q	flow of proportional valve, m^3/h
K_q	gain of proportional valve flow
K_c	pressure gain of the proportional valve flow
A_p	piston area of the control chamber of the hydraulic cylinder, m^2
x_p	piston displacement of hydraulic cylinder, m
C_p	internal leakage coefficient of hydraulic cylinder
V_p	volume of the control chamber of the hydraulic cylinder, V
β_e	elastic modulus of liquid, MPa
F_p	output power of hydraulic cylinder, N
m_p	total mass of the piston and the load, kg
B_p	damping coefficient of the piston, N/(m/s)
K_p	stiffness of the load spring, N/m
i_m	armature current, A
r_{ma}	motor armature resistance, Ω
L_m	motor armature inductance, H
u_b	voltage across the battery, V
r_b	battery resistance, Ω
r_c	wire resistance at both ends of capacitor, Ω
C	capacitor capacitance, F
u_c	voltage across the capacitor C, V
F_m	output force of vacuum booster, N
X	input displacement, m
X_m	piston stroke, m
k_1	equivalent stiffness of the system
M_T	pedal mass, kg
C_T	equivalent damping coefficient of the pedal, N/(m/s)
K_T	stiffness of the pedal return spring, N/m
F_{in}	input force to the vacuum booster, N
τ_p	time constant
k	magnification of the vacuum booster