Energy 114 (2016) 683–692

Contents lists available at ScienceDirect

Energy

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

A hydraulic hybrid propulsion method for automobiles with self-adaptive system

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ARTICLE INFO

Article history:
Received 31 December 2015
Received in revised form
14 July 2016
Accepted 13 August 2016

Keywords:
Hydraulic hybrid vehicle
Hydraulic transformer
Hydraulic regenerative braking
Energy efficiency
Cross-feedback control

ABSTRACT

A hydraulic hybrid vehicle with the self-adaptive system is proposed. The mode-switching between the driving mode and the hydraulic regenerative braking mode is realised by the pressure cross-feedback control. Extensive simulated and tested results are presented. The control parameters are reduced and the energy efficiency can be increased by the self-adaptive system. The mode-switching response is fast. The response time can be adjusted by changing the controlling spool diameter of the hydraulic operated check valve in the self-adaptive system. The closing of the valve becomes faster with a smaller controlling spool diameter. The hydraulic regenerative braking mode can be achieved by changing the hydraulic transformer controlled angle. Compared with the convention electric-hydraulic system, the self-adaptive system for the hydraulic hybrid vehicle mode-switching has a higher reliability and a lower cost. The efficiency of the hydraulic regenerative braking is also increased.

1. Introduction

The reduction of the fuel consumption as well as the exhaust emissions becomes more and more important for road vehicles [1]. Hybrid vehicles are an alternative for reducing fuel consumption and exhaust emissions [2]. The hybrid electric vehicles have received the most attention for the light-duty vehicle [3]. For the heavy-duty vehicle, the hydraulic hybrid vehicles (HHV) are more cost effective [4]. Further, the hydraulic hybrid propulsion system presents the best method for the regenerative braking, especially for the high stop-and-go frequency operations [5,6]. The architecture of the hydraulic hybrid propulsion system contains the parallel one [7], the series one [8] and the hydro-mechanical transmission [9]. All the hydraulic hybrid propulsion systems are composed of the hydraulic pump/motor unit. The control of the hydraulic pump/motor unit can be divided into the hydraulic valve controlled type [10] and the hydraulic displacement controlled type [11]. The hydraulic valve controlled type has a faster response and a relatively larger throttle energy loss. The hydraulic displacement controlled type achieves higher energy efficiency [12]. However, the efficiency is still lower than the electric hybrid system.

To further increase the efficiency, the hydraulic hybrid propulsion system powered by a hydraulic common pressure rail is designed with the hydraulic transformer (HT) [13]. The HT is an energy efficient, throttle-less control approach for the hydraulic hybrid propulsion system [14]. The hydraulic power is usually supplied by a hydraulic free-piston engine with a higher efficiency [15]. The performance comparison between the conventional vehicle and the HHV with the HT has been investigated. The results indicated that the HHV with the HT has advantage in fuel economy [16]. The theory of limit cycles has been applied to the analysis of the HHV [17]. The existence of limit cycle and the stability of equilibrium points in the system were discussed in detail. The flow fluctuation of the HT is larger than the hydraulic pump. Chen and co-researchers have indicated that the series hydraulic accumulator is much superior to the parallel hydraulic accumulator in terms of pulsation damping of the HT [18]. An effective method for the parameter design of the HHV with the HT has been studied. The results indicate that the parameter design for the HHV with the HT becomes more flexible [19].

The high power density of the hydraulic hybrid propulsion system is an attractive advantage for the regenerative braking of a

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http://dx.doi.org/10.1016/j.energy.2016.08.042
0360-5442/

Nomenclature

A	vehicle frontal area
A_{pipe}	pipe cross-sectional area
A_P	piston sectional area
A_V	action area of the spool
B_O	oil bulk modulus
c	viscous damper coefficient
c_{Vf}	damping coefficient
C_D	air drag coefficient
C_V	flow coefficient
D	main spool diameter
d	controlling spool diameter
f	rolling resistance coefficient
F_T	longitudinal tire force
F_C	external spool control force
F_{Vfl}	flow force
F_{VK}	spring force
g	acceleration of the gravity
i_0	final ratio of the drive train
J_{HT}	inertia moment of the shaft-cylinder-piston assemble
k_{RV}	slope coefficient of valve static characteristics
K_m, K_P	leakage coefficient
m	vehicle mass
m_V	main spool mass without spring mass incorporated
m_v	controlling spool mass
n_{HT}	hydraulic transformer speed
n_m	hydraulic motor speed
p	system pressure
p_1	operating pressure of the self-adaptive system
p_2	operating pressure of the self-adaptive system
p_A	pressure of the high-pressure rail
p_m	differential pressure across the hydraulic motor
p_{pipe}	pressure of the hydraulic pipe
p_P	pressure of the piston bore
p_{pr}	gas precharge pressure
p_{RV}	valve opening pressure
p_{Vin}	pressure at the inlet port
p_{Vout}	pressure at the outlet port
P_{VX}	pressure at the controlling port
Q	instantaneous flow of the control volume
Q_V	flow rate through the check valve
Q_{lP}	leakage flow
Q_m	flow delivery of the hydraulic motor
Q_{pipe}	flow delivery of the hydraulic pipe
Q_{rated}	hydraulic power engine rated flow
r_{wheel}	wheel radius
R	radius of the rotating group
s	Laplace operator
S_V	cross-section area of the spool
t	time
t_1	time when the pressure declines during mode-switching
t_2	time when the hydraulic operated check valve begins closing
t_3	time when the high pressure switches to the low pressure
t_4	time when the valve achieves the maximum flow area
t_e	operation time of the engine
T_D	dynamic frication torque
T_L	load torque
T_m	total torque in the hydraulic motor
T_{mB}	damping friction torque
T_{mI}	inertial torque
T_S	breakout friction torque
T_T	external torque
T_P	driving torque applied by each piston
u	vehicle speed
u_{err}	difference between reference vehicle speed and vehicle speed
u_r	required vehicle speed
u_{ref}	reference vehicle speed
V	instantaneous volume
V_0	volume when the piston displacement is zero
V_{AC}	fluid volume within the accumulator
V_{AC0}	accumulator capacity
V_m	displacement of the hydraulic motor
V_{HT}	displacement of the HT basal
x	hydraulic pipe length
x_{v1} and x_{v2}	controlling spool displacements
x_{V1} and x_{V2}	main spool displacements
x_{gap}	gap between the spools
X_{PV}	transfer function for the swash plate motion
x_V	main spool displacement
x_v	controlling spool displacement
Z	piston number

Greeks

α	swash plate angle
β	road grade
φ	controlled angle of the swash plate
θ	located angle of the piston
η_{mm}	mechanical efficiency of the hydraulic motor
ρ_O	hydraulic oil density
ω	natural frequency
ς	damping ratio
γ	specific heat ratio
σ	mass factor of rotating components

Abbreviations

CPR	Common pressure rail
EH-HHV	HHV with the electric-hydraulic system
HHV	Hydraulic hybrid vehicle
HT	Hydraulic transformer
SA-HHV	HHV with the self-adaptive system

vehicle with the frequent stops [20]. The propulsion mode of the HHV needs to be changed from the driving mode to the hydraulic regenerative braking mode. In the conventional design, the mode-switching is realised by an electric-hydraulic slide valve [16]. An electric control signal from the ECU with the braking pedal angle as the feedback is necessary. The HT controlled angle also needs to be adjusted [19]. It makes the mode-switching control become complicated. Further, an unavoidable throttle loss is caused by the electric-hydraulic slide valve due to the larger flow through the valve.

This paper presents a hydraulic hybrid propulsion system for automobiles with a self-adaptive system. The mode-switching between the driving mode and the hydraulic regenerative braking mode is realised by the pressure cross-feedback control. The switching is only controlled by the HT controlled angle. The operation characteristics during the mode-switching are investigated.