HIGH TECHNOLOGY LETTERS | Vol. 20 No. 1 | Mar. 2014 | pp. 97 ~ 102

doi:10.3772/j.issn.1006-6748.2014.01.016

Operation control strategy of series-parallel hydraulic hybrid vehicle①

Zhao Lijun (赵立军)②***, Ge Zhuhong*, Luo Nianning*, Liu Xinhui**
(*School of Automobile Engineering, Harbin Institute of Technology, Weihai 264209, P. R. China)
(**College of Mechanical Science and Engineering, Jilin University, Changchun 130025, P. R. China)

Abstract

A series-parallel hydraulic hybrid system applied to public buses is put forward, and parameters of key components are analyzed and determined. Energy management strategy based on logic threshold is designed which is aimed at efficient operation of the overall system considering the operational characteristic of the components and taking the curves of engine, hydraulic pump/motor and hydraulic pump as the main design basis; regenerative control strategy which makes regenerative brake system and frictional brake system work harmoniously is designed to raise recovery rate of regenerative brake energy. System dynamic modeling and simulation results show that the energy control strategy designed here is able to adapt system to changes of working condition and switch the operating mode reasonably. The regenerative braking control strategy is effective in raising the utilization of energy and improving fuel economy.

Key words: series-parallel configuration, hydraulic hybrid vehicles, vehicles for public transport, operation control strategy, regenerative brake

0 Introduction

As energy crisis and environmental problems become more and more serious, hybrid vehicle technology arouses increasing attention of foreign governments and automobile research institutes. Hydraulic transmission hybrid technology which is one of the important branches of the hybrid vehicle research is widely applied in mid-sized, heavy vehicles and engineering machinery taking the advantage of its high power density and low cost. However the energy-storage component which has a low energy density in the system is not able to work as the auxiliary power source for a long time. Besides, urban buses start and stop constantly and their speed changes dramatically[1]. As a result, traditional operation control strategy for hybrid vehicle cannot work effectively.

A novel series-parallel hybrid system configuration which is suitable for the working condition of urban buses is presented aiming at solving the above-mentioned problems. On the basis of optimization of the basic gear ratio of planetary gear train and the transmission ratio of the transfer case, energy management strategy based on logic threshold[2] is designed to get the engine working efficiently and carry out appropriate drive mode selection. Meanwhile regenerative control strategy based on ideal braking force distribution is put forward to recover braking energy effectively. In light of existing resources, this research is based on the refitment of model NJ6488.

1 The working principle of the series-parallel hydraulic hybrid system

The series-parallel hybrid transmission system is composed of engine, hydraulic variable pump, hydraulic accumulator, hydraulic variable pump/motor, gearbox, planetary gear train, driving axle and relative control system , as shown in Fig. 1. In this paper, a

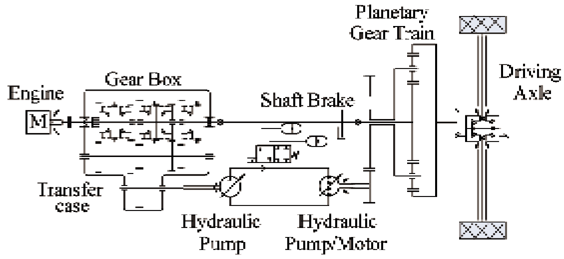

Fig. 1 Series-parallel hydraulic hybrid system

① Supported by the National Natural Science Foundation of China (No. 50875054) and Weihai Science and Technology Development Plan Project (No. 2012DXGJ13).

② To whom correspondence should be addressed. E-mail: zhaolijun@hitwh.edu.cn

Received on Oct. 23, 2012

new configuration is adopted with engine connected to the sun gear, pump/motor connected to the carrier gear and drive train linked to the ring gear. This configuration has better speed regulation performance and better suits the working condition of urban buses in comparison with Prius[3]. As shown in Fig. 2, dramatic speed changes at the driving axle do not cause significant changes in the operation state of engine.

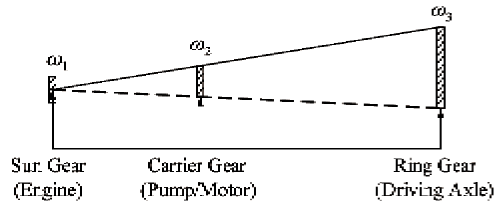

Fig. 2 Speed regulation characteristic of the new configuration

The hybrid system selects the following driving modes[4] under different driving conditions: pump/motor only, engine only, charging mode, series-parallel mode, pump/motor assist and regenerative braking.

2 Parameter selection of key components

(1) The selection of hydraulic accumulator model and its operating pressure range

The maximum operating pressure of a hydraulic accumulator is not allowed to be higher than that of the pump/motor. When selecting the pre-charge pressure of accumulator, the efficiency of regenerative braking system needs to be taken into consideration[5].

The selection of accumulator volume should make sure that the regenerative system can recover the kinetic energy of the vehicle with 80% of its top speed in its driving condition as

$$E_{Acc} = \frac{p_0 V_0}{n-1}\left[\left(\frac{p_0}{p_2}\right)^{\frac{1-n}{n}} - 1\right] \geqslant \frac{1}{2} m (0.8 u_{max})^2 \qquad (1)$$

here, u_{max} is the maximum speed (m/s), p_0 is the pre-charge pressure (MPa), V_0 is the volume of accumulator under pre-charge pressure, p_2 is the maximum operating pressure, n is the polytropic index and m is the complete vehicle mass.

(2) The optimal selection of the basic gear ratio of planetary gear train α

The aim of optimal selection of the basic gear ratio of planetary gear train α is to gain the best comprehensive system performance[6]. On geometrical basis, the function[7,8] that defines the rotational speeds of the planetary gear set constitutes a plane in space. As illustrated in Fig. 3, when Section A has the largest projected area in three coordinate planes, the system gets the best performance. In order to achieve this, Section A and Section B determined by G, H, I should be parallel, namely the included angle θ between Section A and Section B should be as small as possible.

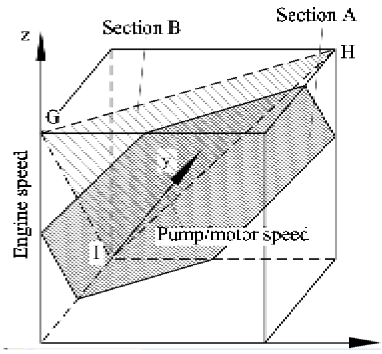

Fig. 3 Relation of rotational speed of planetary gear train

As it can be seen from Fig. 4, when $\alpha = 1$, θ has its minimum value. Therefore α takes 1 as its value in this design.

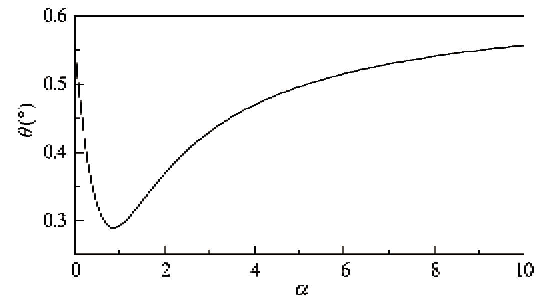

Fig. 4 The relation between θ and α

(3) The selection of hydraulic pump/motor

When starting up or regenerative braking[9], pump/motor must be able to provide torque requested from powertrain. The displacement of pump/motor is determined by the following expressions:

$$\min D_{p/m} = \max[D_{max1}, D_{max2}, D_{max3}] \qquad (2)$$

$$D_{max1} = \frac{(mgf + \delta m a_{max}) \cdot R}{i_0} \cdot \frac{1+\alpha}{\alpha} \cdot \frac{1}{i_4} \cdot \frac{2\pi}{p_2} \qquad (3)$$

$$D_{max2} = \frac{0.1 mg \cdot R}{i_0} \cdot \frac{1+\alpha}{\alpha} \cdot \frac{1}{i_4} \cdot \frac{1}{p_1} \qquad (4)$$

$$D_{max3} > \frac{(F_f + F_w + F_a) \cdot R}{i_0} \cdot \frac{1+\alpha}{\alpha} \cdot \frac{1}{i_4} \cdot \frac{2\pi}{p_2} \qquad (5)$$

here, a_{max} is the maximum acceleration, i_0 is the final drive ratio, i_4 is the ratio between the output shaft of pump/motor and the carrier gear of planetary gear set, m is the complete vehicle mass, R is the tire radius, F_f is the rolling resistance, F_w is the air resistance, F_a is the acceleration resistance, δ is the rotational inertia conversion factor, α is the basic gear ratio of planetary gear train, p_1 is the minimum operating pressure and p_2 is the maximum operating pressure.

(4) The selection of hydraulic variable pump

The selection of hydraulic pump should meet the requirement of engine power regulation. The maximum power of pump needs to be higher than the maximum regulation power of demand. The pump must be ensured not to be overspeed in the working speed range of engine since it is directly linked to engine. In the overall matching of components, the displacement of pump is larger than that of pump/motor and is finally determined by the results of simulation and actual product model.

(5) The selection of transfer case ratio

When the pump is working at 25% ~100% of its rated speed, its efficiency is relatively high[10]. In addition, the overall efficiency of pump increases with current displacement. The influence of pressure on efficiency is comparatively small, but in practical application pressure change is controlled within the range of 20% ~ 80% of the maximum working pressure. For these reasons, the selection of transfer case ratio should ensure that the pump operates in a state of middle or high pressure, large displacement and high rotational speed in order to gain a high overall efficiency.

On the basis of the proposed selection rules, a backward simulation vehicle model is established with Simulink to find out optimized matching results. Major parameters of the vehicle are listed in Table 1.

Table 1 Parameter list for series-parallel hybrid vehicle

	Name	Value
Basic parameters of vehicle	Tire radius	0.3556m
	Air drag coefficient	0.6
	Frontal area	6m^2
	Vehicle mass	2500kg
Gearbox	Transmission ratio	5.19,3.89,2.26,1.42,1,5.69
Driving axle	Final drive ratio	4.875
Hydraulic accumulator	Volume	25L
	Max working pressure	20MPa
	Min working pressure	8MPa
Planetary gear train	Basic gear ratio	1
Ratio between pump/motor and carrier gear	Transmission ratio	2
Transfer case ratio	Transmission ratio	0.3
Hydraulic pump	type	A4VSG60
Hydraulic pump/motor	type	A4VG55

3 Design of operating control strategy

3.1 Energy management control strategy based on logic threshold

There are several different driving modes in the series-parallel hydraulic hybrid system. Thus, its adaptability to complex driving condition is better than parallel configuration. Series-parallel mode can effectively operate the engine in those operating points that entail minimum fuel use for a given power request. The set of operating points that fulfill this criterion is defined as the economy line. Owing to the existence of planetary gear coupler, the engine has no direct mechanical connection with wheels and this contributes to the complexity of the establishment of simulation model. To select proper driving mode according to driving condition is the major task of energy management strategy. The ratio of transfer case has been optimized in the preceding text, hence pump and pump/motor are ensured to work with high efficiency, as shown in Fig. 5. On this basis, the essence of energy management strategy is to optimize the efficiency of engine[11,12].

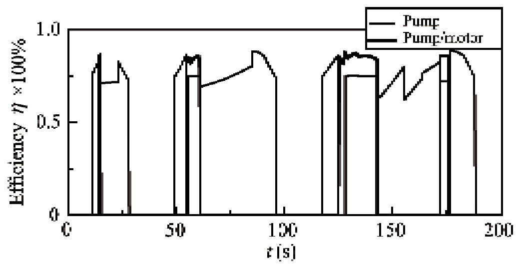

Fig. 5 The efficiency of pump and pump/motor under ECE-15 driving cycle

Logic threshold parameters and the rules of driving mode selection are described below.

In this paper, the area between equipower lines P_{e_optlo}, P_{e_opthi} and medium speed range in the engine fuel map is defined as the efficient operation area of engine[12].

When starting up, if the pressure in the accumulator is above the lowest operating pressure, pump/motor only mode is applied. After launch process, when the power request is lower than P_{e_optlo}, and if pressure in the accumulator is lower than the minimum working pressure, charging mode is activated. When the requested power is higher than P_{e_opthi}, and if the pressure in the accumulator is higher than the requested working pressure, parallel driving mode is adopted. If the requested power is between P_{e_optlo} and P_{e_opthi}, engine only mode is selected.

Hydraulic accumulator has better working cycle durability than battery. Therefore in hydraulic hybrid system, there is no need to take up charge-sustaining strategy which is widely used in hybrid electric system[13]. Shifting the driving mode is realized by evaluating threshold parameters like speed u, requested power P_{req}, pressure p in hydraulic system. The specific control strategy is illustrated in the following Fig. 6.

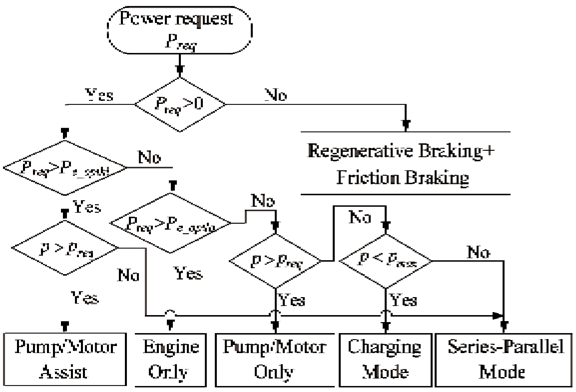

Fig. 6 Control logic for mode switching

3.2 Regenerative braking control strategy based on ideal braking force distribution

Regenerative braking strategy[14] is based on such an idea: when the deceleration is lower than 0.1g, only rear axle provides regenerative braking force. When the deceleration is higher than 0.1g, the braking force is distributed according to the ideal front/rear axle braking force distribution line.

Regenerative braking control logic is as follows:

(1) If $Z \leqslant 0.1$ AND $p_{min} < p < p_{max}$ Then $T_{reg} = T_{req}$; $T_{fri} = 0$;

(2) If $0.1 < Z \leqslant 0.7$ AND $p_{min} < p < p_{max}$ Then $T_{fri} + T_{reg} = T_{req}$;

(3) If $Z > 0.7$ AND $p_{min} < p < p_{max}$ Then $T_{fri} = T_{req}$.

Here, Z is braking intensity, T_{req} is requested braking torque, T_{reg} is regenerative braking torque, T_{fri} is friction braking torque.

4 Simulation analysis of operation control strategy

In order to verify the validity of the operation control strategy mentioned above, a backward hybrid vehicle model is established with Simulink[15,16]. Simulation is carried out under ECE-15 driving cycle (shown in Fig. 7) which is close to the actual driving condition of urban buses. Simulation results are shown in Fig. 8, Fig. 9 and Fig. 10.

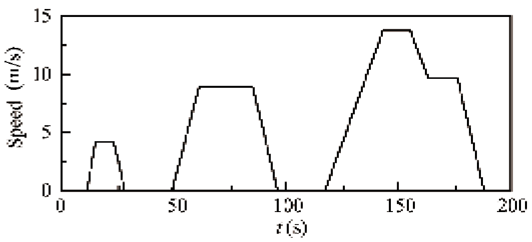

Fig. 7 ECE-15 driving cycle

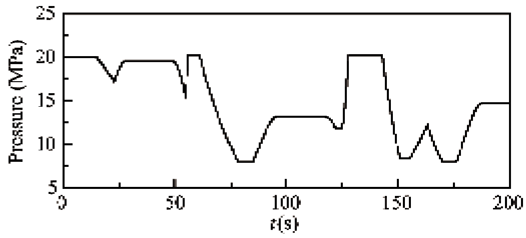

Fig. 8 The pressure of accumulator

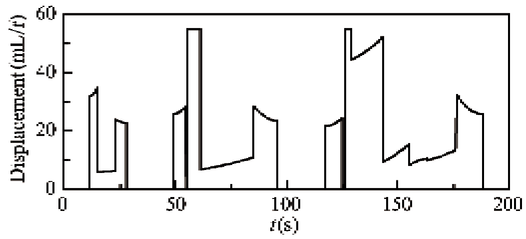

Fig. 9 The displacement of pump/motor

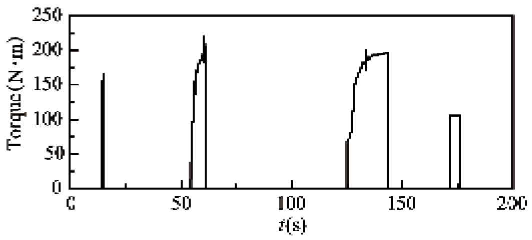

Fig. 10 The torque of engine

As can be seen from Fig. 10, when the pump/motor gives tractive force to the wheels only, the engine is kept idle. In this way, fuel consumption is reduced. When the engine is on, its efficiency is improved in a way that operating points is shifted towards efficient area of fuel map by hydraulic transmission system. The pressure in the accumulator changing in a wide range indicates that energy is recovered and reused effectively. Fig. 11 and Fig. 12 shows the distribution of engine operating points. After the operation control strategy is applied, most of the operating points of engine fall in the low fuel consumption area and this proves that the strategy is effective.

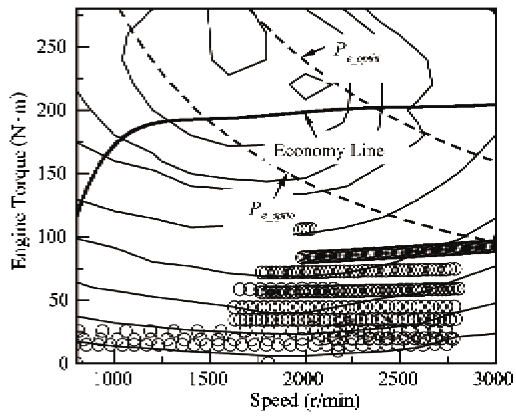

Fig. 11 Operating points of traditional vehicle

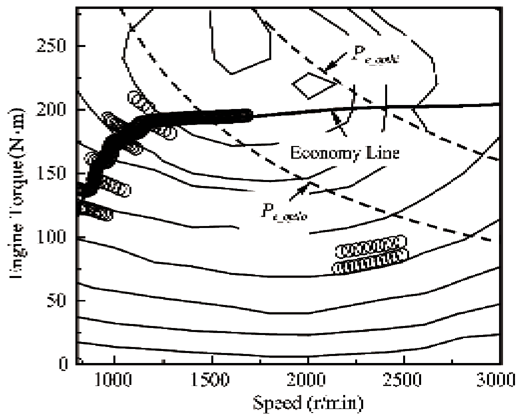

Fig. 12 Operating points of hybrid vehicle

In comparison with traditional vehicle with similar dynamic performance, the operation control strategy can effectively reduce fuel consumption without sacrificing dynamic performance. For this particular driving cycle, with this operation strategy, a theoretical fuel reduction of 30% is achieved.

5 Conclusions

A novel series-parallel configuration which is suitable for working conditions of urban buses is put forward. And then the selection rules of key components are proposed. On this basis, energy management strategy is designed according to the fuel consumption map of engine and overall efficiency maps of pump and pump/motor. And regenerative braking strategy is designed based on ideal braking force distribution. Simulation results show that energy management strategy can effectively adjust the working state of engine and implement proper driving mode in complex driving conditions. Besides, the regenerative braking strategy can recover braking energy efficiently to raise the utilization of energy and bring down fuel consumption. This research comes up with a new energy saving solution to urban buses which has several advantages over electrical hybrid system. Further study will focus on reliability of hydraulic system and building hydraulic hybrid test rig.

References

[1] Luo L M, Cao Z C, Zhang Z Y. Urban bus driving cycle and braking characteristic analysis. *Beijing Automotive Engineering*, 2006, (2): 21-23 (in Chinese)

[2] Pu J H. A Study on Optimal Energy Management and Control strategy for hybrid electric vehicles: [Ph. D dissertation]. Shanghai: Shanghai Jiao Tong University, School of Mechanical Engineering, 2007. 46-61 (in Chinese)

[3] Liu W J. Study on the Optimization of Control Strategy for a Parallel-Series Hybrid Electric Vehicle: [M. S. dissertation]. Chongqing: Chongqing University, School of Mechanical Engineering, 2007. 7-9 (in Chinese)

[4] Chen S L, Wang L F, Liao C L, et al. Realization of an energy management strategy for a series-parallel hybrid electric vehicle. In: IEEE Vehicle Power and Propulsion Conference, Harbin, China, 2008. 1-5

[5] Sun H. Research and Optimization on the Key Technologies of Secondary Regulation Hydrostatic Transmission Vehicles: [Ph. D. dissertation]. Harbin: Harbin institute of technology, School of Mechanical Engineering, 2009. 18-23 (in Chinese)

[6] Bu X, Du A M, Xue F. Theoretical study and simulation on planetary gear set for hybrid electric vehicle. *Automotive Engineering*, 2006(9): 834-837 (in Chinese)

[7] Szumanowski A. Hybrid Electric Vehicle Drives Design Edition Based On Urban Buses. Beijing: Beijing Institute of Technology Press, 2007. 14-20 (in Chinese)

[8] Kessels J T B A, Koot M W T. Online energy management for hybrid electric vehicles. *IEEE Transactions on Vehicular Technology*, 2008, 57: 3430-3432

[9] Liu T, Jiang J H. Energy control strategy research of parallel hydraulic hybrid vehicle. *Journal of Southeast University*, 2010, 40(1): 111-113 (in Chinese)

[10] Yao H X. Analysis of hydraulic driving system of construction equipment chassis (1). *Road Machinery & Construction Mechanization*, 2003, (1): 60-61 (in Chi-

nese)
[11] Kleimaier A, Schroder D. An approach for the online optimized control of a hybrid powertrain. *Advanced Motion Control*, 2002, (1): 215-220
[12] Wu J, Zhang C H, Cui N X, et al. An improved energy management strategy for parallel hybrid electric vehicle. In: Proceedings of the 6th World Congress on Intelligent Control and Automation, Dalian, China, 2006. 8340-8343
[13] Wang W D, Xiang C L, Han L J, et al. A research based on SOC retaining-based energy management strategy for PSHEV. *Automotive Engineering*, 2011, 33(5): 373-376 (in Chinese)
[14] Gan Z X. Study on control strategies of regenerative braking system for HEV bus based on ABS: [M. S. dissertation]. Changchun: Jilin University, School of Automotive Engineering, 2009. 25-26 (in Chinese)
[15] Liu J M, Peng H. Modeling and control of a power-split hybrid vehicle. *IEEE Transactions on Control System Technology*, 2008, 16: 1242-1244
[16] Wang W, Liu X H. Optimization and simulation of energy management strategy for a parallel-series HEV. In: International Conference on Computer Application and System Modeling, Taiyuan, China, 2010. 3: 488-491

Zhao Lijun, born in 1975. He received his B. S. and Ph. D. degrees in School of Automotive Engineering of Harbin Institute of Technology in 1997 and 2011 respectively. He received his M. S. in School of Automotive Engineering of Harbin Institute of Technology at Weihai in 2003. His research interests include the hydraulic hybrid technology and special vehicle technology.