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OPTIMAL TORQUE MANAGEMENT STRATEGY FOR A PARALLEL HYDRAULIC HYBRID VEHICLE

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ABSTRACT–The hydraulic hybrid vehicle (HHV) is an application of hydrostatic transmission technology to improve vehicle fuel economy and emissions. A relatively lower energy density of hydraulic accumulator and complicated coordinating operations between two power sources require a special energy management strategy to maximize the fuel saving potential. This paper presents a new type of configuration for parallel HHV to minimize the disadvantages of the hydraulic accumulator, as well as a methodology for developing an energy management strategy tailored specially for PHHV. Based on an analysis of the optimal energy distribution between two power sources over a representative urban driving cycle with a Dynamic Programming (DP) algorithm, a fuzzy-based optimal torque management strategy is designed and developed to control the torque distribution. Simulation results demonstrates that the optimal torque management strategy maximizes the advantages of this hybrid type of configuration, and the high power density characteristics of hydraulic technology effectively improve the robustness of the energy management strategy and fuel economy of the PHHV.

KEY WORDS: Hydraulic hybrid vehicle, Pump/motor, Dynamic programming, Torque management, Fuzzy logic

1. INTRODUCTION

The search for improved fuel economy, reduced emissions, and affordable vehicles, without sacrifice of vehicle performance, safety, reliability, and other conventional vehicle attributes, has made the hybrid technology one of the challenges for the automotive industry. As an important branch of hybrid technology, the hydraulic hybrid vehicle has increasingly aroused the attention of the research institutions and automotive manufacturers all over the world (Wei, 2006). Hydraulic hybrid systems, using a combination of an internal combustion engine (ICE) and hydraulic pump/motor, have the potential for improving fuel economy by operating the ICE in the optimum efficiency range and making use of regenerative braking during deceleration. A hydraulic accumulator has the advantage of a high power density and the ability to accept high rates and high frequencies of charging and discharging, both of which are not favorable for batteries (Lee and Sul, 1998; Johnson *et al.*, 2000); therefore, hydraulic hybrid technology is well-suited for luxury passenger cars, sport utility vehicles, light duty trucks and heavy-duty trucks. There is a wealth of literature focused on energy control of hybrid electric vehicles, but the publications devoted to hydraulic propulsion options are relatively scarce (Jung *et al.*, 2003; Lin *et al.*, 2001a, 2001b; Pu *et al.*, 2005; Park *et al.*, 2005; Assanis *et al.*, 2000; Buie *et al.* 2004).

Early energy management strategies for hybrid vehicle attempted to use engine universal performance characteristics map to design control strategies. Buchwald *et al.* (1979) evaluated three different strategies on city buses by considering simple vehicle acceleration-deceleration profiles. Wu *et al.* (1985) proposed a strategy for passenger cars based on dividing the hydraulic accumulator volume into two parts, one for regeneration and the other for road-decoupling. Bin and Lin (2004) proposed an optimal power management strategy for a hydraulic hybrid delivery truck. However, realistic vehicle operating conditions vary over in a very wide range, the efficiencies of both the engine and the hydraulic pump/motor are strong functions of their respective operating conditions, and the lower energy density of hydraulic accumulator and complicated coordinating operation between the primary power source and assistant power source require a carefully designed energy management strategy to coordinate all the powertrain components in an optimal manner and maximize the fuel-saving potential while satisfying performance constraints.

In this paper, a new type of configuration for parallel hydraulic hybrid vehicles is presented. The supply oil pump is introduced to minimize the disadvantages of

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Corresponding author. e-mail: sunhuinievana@163.com hydraulic accumulators' lower energy density and make the engine work in a better economy region through initiative filling pressure function. The Dynamic Programming method is used to investigate the optimal torque distribution between the engine and hydraulic pump/motor over a representative urban driving cycle. The results of the DP are studied to extract the main features of the optimal control law. Subsequently, the fuzzy-based optimal torque strategy based on the DP optimization results is designed and developed to control the torque distribution between the engine and hydraulic pump/motor. Simulation results demonstrate its effectiveness in further improving the fuel economy of PHHV.

2. CONFIGURATION AND MATHEMATICAL MODEL FOR THE NEW TYPE OF PHHV

2.1. System Configuration

Figure 1 presents the new type of configuration for PHHV.

This front-wheel-drive hydraulic hybrid vehicle consists primarily of an internal combustion engine, a high pressure accumulator, low pressure reservoir, supply oil pump, and a variable displacement hydraulic pump/motor unit. The primary power source is the same diesel engine used in the conventional vehicle. The transmission, propeller shaft, and the differential and driving shaft are the same as those in the conventional vehicle. The hydraulic pump/motor and supply oil pump are coupled to the propeller shaft via a planetary gear system. During deceleration, the hydraulic pump/motor decelerates the vehicle while operating as a pump to capture the energy normally lost to friction brakes in a conventional vehicle. Also, when the vehicle brake is applied, the hydraulic pump/motor uses the braking energy to charge the hydraulic fluid from a low pressure hydraulic accumulator into a high-pressure accumulator, increasing the pressure of the nitrogen gas in the high pressure accumulator. The high pressure hydraulic fluid is used by the hydraulic pump/motor unit to generate torque during the next vehicle acceleration (Kepner *et al.*, 2002; Hewko and Weber, 1990). It is designed and sized to capture braking energy from normal, moderate braking events and is supplemented by friction brakes for aggressive braking.

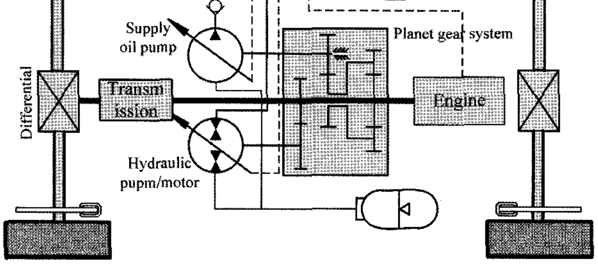

Figure 1. Configuration of the PHHV.

The front-wheel-drive hydraulic hybrid vehicle has a greater potential in braking energy regeneration and better braking performance because of the increase of the front axle load during the course of braking. The introduction of the supply oil pump minimizes the lower energy density disadvantage of the accumulator and makes the engine work in high efficiency region through the initiative filling function. Meanwhile, the accumulator's SOC is controlled so that it is less than 0.5, which ensures that the accumulator have enough space for recycling braking energy.

2.2. Mathematical Model of the PHHV

The overall mathematical modeling of the PHHV consists of the mathematical models of several subsystems including the primary power source system, assistant power source system, hydraulic accumulator system, and the vehicle dynamics, *et al.*

(1) The longitudinal dynamic model of the vehicle is

$$T_w=\left[Gf+\frac{G_d\cdot A\cdot v^2}{21.15}+\delta M\frac{dv}{dt}\right]r \tag{1}$$

The speed and torque relationship between the engine and hydraulic pump/motor are as follows:

$$T_w=\eta_T(T_e+\eta_{P/M}T_{P/M}-T_P)+T_b \tag{2}$$

$$n_w=\frac{n_e}{i_{gb}i_{fd}}=\frac{n_{P/M}}{i_{gb}i_{fd}} \tag{3}$$

where $\eta_T=\begin{cases}\eta_T & T_w\geq 0\\ 1/\eta_T & T_w<0\end{cases}$, $\eta_T=\eta_{gb}\eta_{fd}\eta_{wh}$.

The speed equation of PHHV is as follows:

$$V(k+1)=v(k)+\frac{1}{M_r}\frac{T_w}{r_d}-\frac{B_wV(k)}{r_d^2}-\frac{V(k)}{|V(k)|}(F_r+F_a(V(k))) \tag{4}$$

where V is the vehicle speed, T_w is the net wheel torque, r_d is the dynamic tire radius, B_w is the viscous damping, F_r and F_a are the rolling resistance force and the aerodynamic drag force, M_r is the effective mass of the vehicle, and n_w, n_e and $n_{p/m}$ are rational speeds of wheel, engine and the hydraulic pump/motor respectively. V_g is the displacement of hydraulic pump/motor, and η_{mh} is the mechanical efficiency of hydraulic pump/motor.

(2) Mathematical model of the engine

The dynamic programming method has the characteristics of high number of states. Thus, a simplified but sufficiently complex vehicle model is developed. The engine dynamics

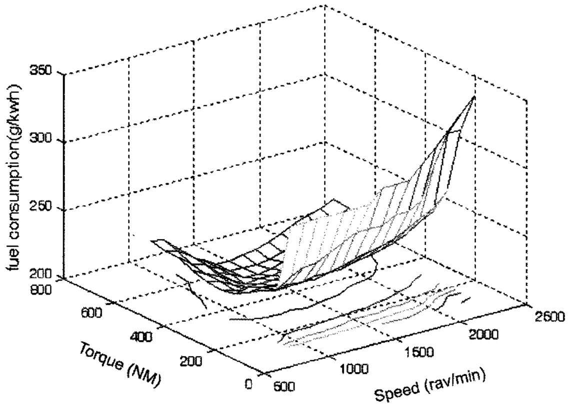

Figure 2. Numerical model of the engine.

are ignored based on the quasi-static assumption. The fuel consumption and emissions generated are static functions of two independent variables, which are the engine speed and engine torque. The numerical model of the engine is shown in Figure 2.

(3) Mathematical model of the hydraulic pump/motor

The hydraulic pump/motor unit was modeled using a slight variation of Wilson's pump theory. Wilson's pump theory relies on simple flow and torque equations, (combined with dimensionless coefficients) to represent volumetric and mechanical losses (Paul *et al.*, 2003; Matheson *et al.*, 2003). The actual volumetric flow rate of a pump/motor is given by:

$$Q=nV_g\eta_{v,p/m} \tag{5}$$

where n is the rotational speed of the hydraulic pump/motor and $\eta_{v,p/m}$ is the volumetric efficiency, which is different depending on whether the unit is operating as a pump or motor.

The actual torque from the pump/motor is given by:

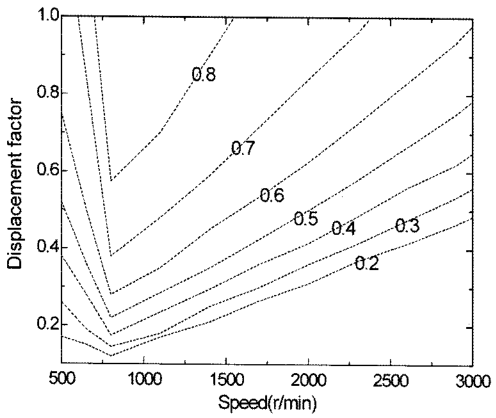

Figure 3. Hydraulic pump/motor efficiency map.

$$T=\frac{V_g\cdot\Delta p}{2\pi}\cdot\eta_{mh} \tag{6}$$

where Δp represents the pressure drop across the unit, and η_{mh} is the mechanical efficiency, which is different for the pump or motor cases.

In order to save the calculation time, the combination of the theoretic model and numerical model method is introduced to build the hydraulic pump/motor model. The efficiency linear interpolation is used to calculate the output torque of the hydraulic pump/motor. The hydraulic pump/motor efficiency map is shown in Figure 3.

(4) Mathematical model of the hydraulic accumulator system

Studies have shown that attempting to model the behavior of the nitrogen gas by using isothermal, adiabatic, or poly-tropic models does not work due to their inability to account for this heat loss. In order to more closely represent the p-v-T characteristics of the nitrogen gas, the Benedict-Webb-Rubin equation is used:

$$p=\frac{RT}{v}+\left(B_0RT-A_0-\frac{C_0}{T^2}\right)\frac{1}{v^2}+\frac{bRT-a}{v^3}+\frac{a\alpha}{v^6} \tag{7}$$

where p, v, and T are the gas pressure, specific volume, and temperature, respectively. All other values in this equation are empirical constants that are specific to nitrogen gas. By differentiating equation (7) with respect to temperature and following the procedure outlined in the Otis Time Constant theory, we arrive at:

$$\frac{dT}{dt}=\frac{T_0-T}{\tau}-\frac{1}{c_v}\left[\frac{RT}{v}\left(1+\frac{b}{v^2}\right)+\frac{1}{v^2}\left(B_0RT+\frac{2C_0}{T^2}\right)\right. \tag{8}$$
$$\left.-\frac{2C_0}{v^3T^2}\left(1+\frac{\gamma}{v^2}\right)e^{-\gamma/v^2}\right]\frac{dv}{dt}$$

Equation (8) is the energy equation for the nitrogen gas, which is numerically integrated to give the temperature-time history, since the volumetric flow rate is known at each time step. This temperature is then put back into equation (7) to give the accumulator pressure history for a process cycle.

3. OPTIMIZATION OF TORQUE DISTRIBUTION CONTROL STRATEGY

Dynamic programming (Bertsekas, 1995) is a powerful tool to solve general dynamic optimization problems. The main advantage is that it can easily handle the constraints and nonlinearity of the problem while obtaining a globally optimal solution. The DP technique is based on Bellman's Principle of Optimality, which states that the optimal policy can be obtained if we first solve a one-stage sub-problem involving only the last stage and then gradually extend to sub-problems involving the last two stages, last three stages, etc. until the entire problem is solved. In this work, the DP method is applied to find the optimal trajectory of vehicle operating modes. Once the system configuration, component design, and driving cycle are fixed, the fuel economy depends only on the strategy for distributing propulsion torque between the two power sources. The objective is to search for the optimum trajectories of control signals, $u(k)$, including the engine command and hydraulic pump/motor command that minimize the fuel consumption of PHHV over the whole driving cycle, i.e.:

$$J=\sum_{k=0}^{N-1} L(x(k),\, u(k))+L_e(k)+L_b(k)+G(x(N)) \tag{9}$$

where L is fuel consumption over a time segment, N is driving cycle length, x, u are the vectors of state variables and control signals respectively, and α, β, γ are the weight coefficients.

This objective function represents a control strategy that determines the optimal vehicle operating mode and torque distribution such that the total energy consumption is minimized while satisfying the desired driving torque and vehicle driving performance. The objective function contains three components:

(1) The engine fuel consumption. This term only represents the fuel consumption if it is assumed that the engine is rotating in a steady state.

$$L(x(k),\, u(k))=P_e(k)*g_e(k)*t \tag{10}$$

(2) The second term is used to compensate for the extra fuel consumption with the frequent engine start/stop and shifting gears.

$$L_c(k)=\alpha(\mathrm{sign}(n_e(k+1))-\mathrm{sign}(n_e(k))) \tag{11}$$

$$L_b(k)=\beta|i(k+1)-i(k)| \tag{12}$$

Frequent engine start/stop and shifting gears will worsen fuel consumption and affect the ride comfort.

(3) In order to match the final value of the accumulator SOC with its initial value, a penalty term is added:

$$G=\gamma(SOC(N)-SOC(0))^2 \tag{13}$$

Based on Bellman's principle of optimality, the Dynamic Programming algorithm is presented as follows:
Step *N-1*:

$$J_{N-1}(x(n-1))=\min_{u(N-1)}\,[L(x(N-1),\, u(N-1)) + L_e(N)+L_b(N)+G(x(N))] \tag{14}$$

Step k, for $0\le k<N-1$

$$J_k^*(x(k))=\min_{u(k)}\,[L(x(k),\, u(k))+J_{k+1}^*(x(k+1))] \tag{15}$$

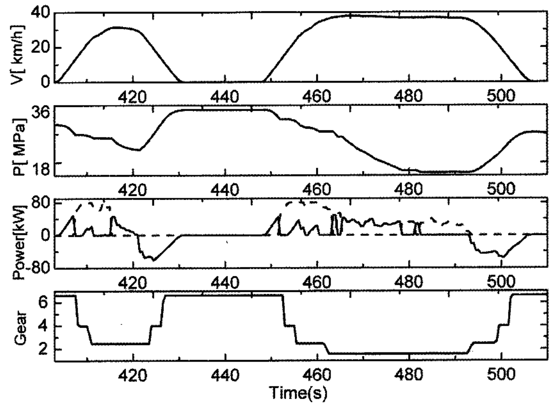

Figure 4. Dynamic Programming results obtained over UUDS driving cycle.

During the optimization, it is necessary to impose the following inequality constraints to ensure safe/smooth operation of the engine/accumulator/motor:

$$\begin{aligned}
&T_{e\_\min}(n_e)\le T_e\le T_{e\_\max}(n_e)\\
&n_{e\_\min}\le n_e\le n_{e\_\max}\\
&T_{P/M\_\min}(n_{P/M})\le T_{P/M}\le T_{P/M\_\max}(n_{P/M})\\
&n_{P/M\_\min}(n_{P/M})\le n_{P/M}\le n_{P/M\_\max}\\
&SOC_{\min}\le SOC\le SOC_{\max}\\
&i\in I=\{1,2,\dots,i_{\max}\}
\end{aligned} \tag{16}$$

For a given initial SOC value, the DP method can be used to find the optimal trajectory of the vehicle operating modes. The different initial accumulator SOCs and various driving cycles may lead to many different numerical solutions that would cover all possible PHHV operating scenarios. Figure 4 presents the optimal trajectories of operating points of the engine and the vehicle operating modes over the UDDS duty cycle when the 'initial SOC is chosen to be 0.8'.

The accumulator pressure is characterized by large fluctuations due to high power flows through the system. Large negative swings of the hydraulic pump/motor power indicate the effective capturing of braking energy. The fuel economy of the DP-optimized hybrid vehicle is better than the initial rule-based control strategy and other control strategies. Therefore, it is felt that the optimization results are reliable and viable. Since the Dynamic Programming algorithm is forward-looking, it requires the knowledge of the future driving conditions, and the resulting optimal control signals are not applicable in practice. However, the optimal control signal trajectories provide a benchmark for evaluating applicable strategies. By analyzing the DP results, we can get useful hints for deriving improved strategies that can be practically implemented.

Clearly, at the beginning of each vehicle launch, the hydraulic pump/motor provides propulsion power alone and avoids forcing the engine to work in the low speed and low load region. With the exception of launch, the engine and pump/motor is used exclusively because engine and the hydraulic pump/motor have the characteristics of higher efficiencies at higher loads.

Whenever the required power demand exceeds the maximum pump/motor power, the engine exclusive working mode is switched. In the meantime, the supply oil pump usually adjusts the engine working load, through the initiative filling pressure function, to keep propulsion component at high-load, high-efficiency region. During the cruise speed stage, the pump/motor is used to satisfy the total power demand whenever there is energy available in the accumulator. In the meantime, the frequent switch between engine work mode and hydraulic pump/ motor work mode needs to be avoided.

4. FUZZY-BASED TORQUE MANAGEMENT STRATEGY

The optimal torque management strategy uses fuzzy logic to build a torque distribution controller based on the analysis of the main features of the optimal control. The supply pump is introduced to minimize the disadvantages of the accumulator's lower energy density, makes the engine work in the best economy region through the initiative filling pressure function.

The two inputs of the fuzzy logic controller are the difference between the optimal torque (corresponding to the current engine rotation speed) and the vehicle requirement torque, and the SOC of the accumulator. The difference between the optimal torque and requirement torque (ΔT) is divided into five fuzzy subsets: {PL, PS, ZERO, NS, NL}. Similarly, the accumulator's SOC is divided in to three fuzzy subsets: {HIGH, MED, LOW}. The two outputs of the fuzzy logic controller are the hydraulic pump/motor's output torque and the supply oil pump's initiative filling pressure torque, while the fuzzy subsets are {LARGE, MED, SMALL, ZERO} and {LARGE, SMALL, ZERO}, respectively. Figure 5 and Figure 6 present the input membership functions and the fuzzy logic block diagram. The hydraulic pump/motor output surface of the fuzzy logic controller is shown in Figure 7.

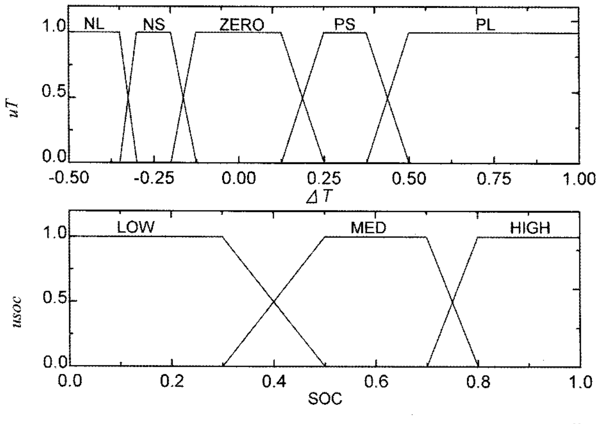

Figure 5. Input membership functions for the scaled ÄT and SOC.

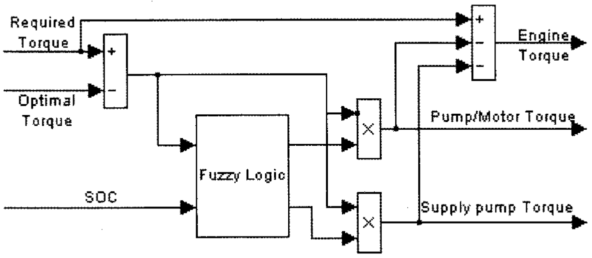

Figure 6. Simplified block diagram of the fuzzy logic controller.

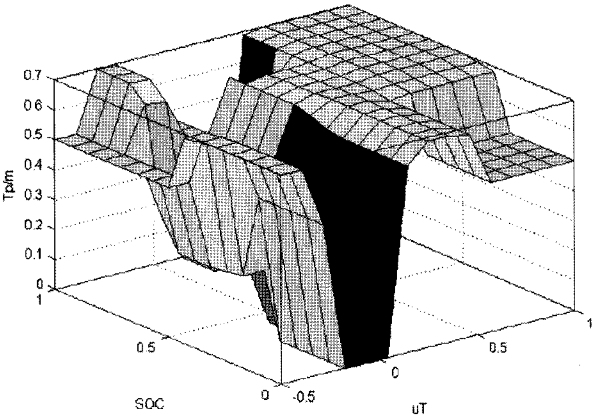

Figure 7. Hydraulic pump/motor surface of fuzzy control.

Table 1 presents a list of if–then rules that represent the optimal torque management strategy based on the analysis of the DP optimization results.

The main principle of the fuzzy-based torque management rules are as follow: (1) ΔT tends to move toward ZERO, which shows that the engine is located in the most economical region and the working point need not to be

Table 1. Fuzzy control principle of the torque management strategy.

Conditions	Conclusion
IFΔT=NL & P=L	Then $T_{P/M}$=L,T_P=Z
IFΔT=NS & P=H	Then $T_{P/M}$=L,T_P=Z
IFΔT=NS & P=M	Then $T_{P/M}$=S,T_P=Z
IFΔT=ZERO	Then $T_{P/M}$=Z,T_P=Z
IFΔT=PL & P~=L	Then $T_{P/M}$=L,T_P=Z
IFΔT=PS & P=H	Then $T_{P/M}$=L,T_P=Z
IFΔT=PS & P=M	Then $T_{P/M}$=Z,T_P=S
IFΔT=PS & P=L	Then $T_{P/M}$=Z,T_P=L

adjusted; (2) ΔT tends to move toward PL, which shows that the engine's efficiency is very low and it should be shut off to make the accumulator provide the driven torque alone; (3) ΔT tends to move toward PS, which shows that the engine is located in the low efficiency region and the initiative filling pressure function of supply oil pump is used to adjust working point onto the optimal curve; (4) when ΔT tends to move toward NL, it should meet the requirement of driving torque instead of fuel economy; (5) when ΔT tends to move toward NS, the accumulator will help to reduce load.

5. SIMULATION RESEARCH

5.1. Simulation Parameters

The vehicle parameters selected in this paper are shown in Table 2.

A back-forward PHHV simulation model, which is implemented in SIMULINK, is shown in Figure 8. HCU mainly is the energy management strategy of PHHV, which includes the optimal torque management strategy mentioned in this study and other basic strategies (such as the braking torque distribution between front axle and rear axle, regeneration braking control algorithm, and so on).

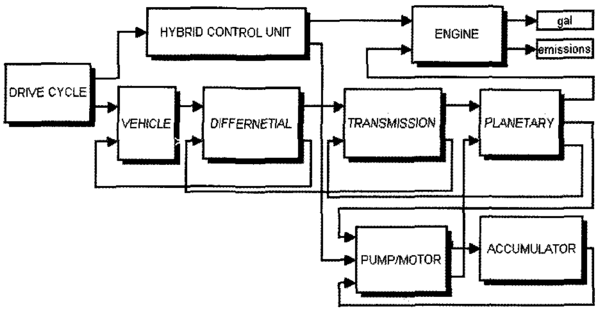

Figure 8. Top-level diagram of the PHHV simulation model.

5.2. Simulation Results

For the given CYC_UDDS driving cycle, simulations were performed using the back-forward PHHV simulation model. An initial-based rules strategy, optimal power management strategy, and fuzzy-based optimal torque management strategies are used to compare the improvement of the fuel economy. The simulation results are shown as follows:

Table 2. Parameters of the vehicle and its components.

Vehicle:	
Wheel diameter	0.5 m
Rolling resistance	0.02
Aerodynamic coefficient	0.65
Frontal area	6.5 m^2
Total vehicle mass	14310 kg
Accumulator system:	
Volume	63L
Max working pressure	35 MPa
Min working pressure	16 MPa
Transmission:	
Gear ratio	6.62, 3.99, 2.47, 1.55, 1
Main gear ratio	4.85
Hydraulic pump/motor:	
Type and displacement	A4VG90
Max Torque	572Nm
Supply oil pump:	
Displacement	40

Hybridization significantly improves the vehicle's fuel economy over the city driving schedule. Hydraulic hybrid technology has unique characteristics of high power density compared to their electric counterparts, which enables the regeneration and reuse of significant amounts of braking energy. The large fluctuations in the accumulator pressure demonstrated the effective regeneration and reuse of braking energy. Even with the initial based-rules, which were never optimized for PHHV, the fuel economy improved to 15.6% compared to the conventional vehicle. However, the relatively low energy density of the hydraulic accumulator can't enable it to drive the vehicle for a long time. The initial based-rules designed the energy distribution strategy based on the static engine universal performance characteristics map and ignored the hydraulic hybrid propulsion system characteristics. Consequently, the energy distribution between primary and assistance sources is unreasonable. The regenerative braking ended early because the accumulator is fully charged. In addition, the frequent switching between the engine mode and pump/motor mode worsens fuel consumption and ride comfort.

The optimal power management strategy proposed by Bin Wu et al. used pump/motor to satisfy the total power demand, whenever there is energy available in the accumulator. If the power requirement is more than what the pump/motor can provide, the engine will supplement the motor power. The based-rules power management strategy ignored the relatively lower efficiency of the engine when the propulsion is switched to the engine work mode at high vehicle speeds, so that the fuel economy potential can't be realized to its fullest.

The fuzzy-based torque management strategy effectively solved the problems in the above strategies. A

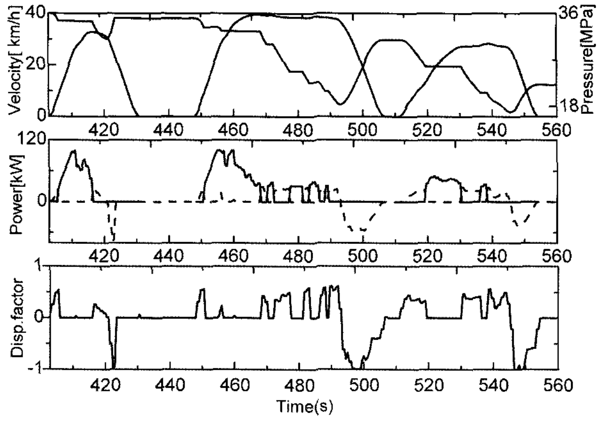

Figure 9. Simulation results of initial rules strategy.

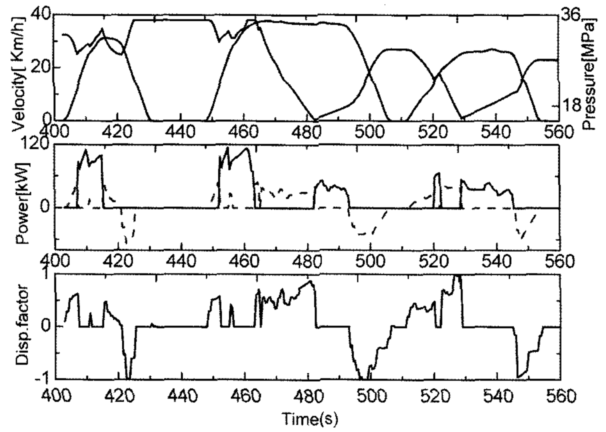

Figure 10. Simulation results of fuzzy-based optimal torque management strategy.

fuzzy logic controller is used to reasonably distribute the propulsion torque between the engine and pump/motor. A hydraulic pump/motor is used to satisfy the total power demand whenever there is energy available in the accumulator. The supply oil pump is introduced to minimize the lower energy density disadvantage of the hydraulic accumulator and move the engine working points into the highest efficiency region through the initiative filling pressure function. Hence, even though practical fuzzy-based torque management strategies cannot achieve the same levels of fuel economy produced by the DP algorithm, they enable a very dramatic increase of the PHHV's ability to realize its fuel saving potential. The implementation of the optimal torque management strategy improved the fuel economy to 32%.

Figure 9 and Figure 10 show the differences between the initial and optimal torque management strategies. With the initial strategy, the hydraulic motor provides mild power assist and operates predominantly with the small displacement factor. With the optimal torque management strategy, the hydraulic motor frequently operates with a much higher displacement factor level, often reaching full-load conditions. The operating points of the engine controlled by initial based-rules are clustered in the mid/low load region. The optimal torque control strategy is able to move most points into the mid/high load zone, which is characterized by the highest efficiencies. Also, the optimal torque control strategy is able to reasonably use the pump/motor to satisfy the total power demand at high vehicle speeds and avoid the frequent switches between the engine work mode and pump/motor work mode, as shown in Figure 10. The engine output torque is smoothed and centralized near the engine optimal torque curve through the reasonable use of supply oil pump's initiative filling pressure function, as shown in Figure 11.

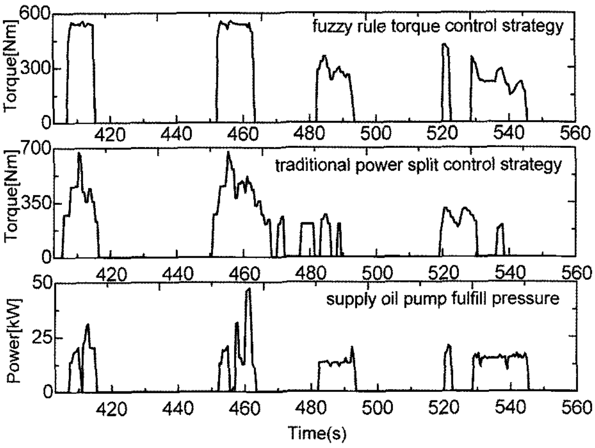

Figure 11. Output torque of engine under different strategies.

The regeneration and reuse of braking energy is the major factor in improving fuel economy of the PHHV. The results in Table 3 indicate the critical role of regeneration and the effective reuse of the braking energy. For the three given energies, the regenerated energy captured during braking reaches similar levels in all cases. How-

Table 3. Summary of simulation results obtained over the UDDS (400~560s).

Configuration	Conventional	Initial base -rules	Optimal power manage -ment	Optimal torque manage -ment
P/M efficient	zero	low	high	high
Drive energy (KJ)	3382	3382	3382	3382
Regen. energy (KJ)	zero	994.4	982.3	936.8
Reuse energy (KJ)	zero	958.5	962.6	1261
Supply energy (KJ)	zero	zero	zero	630.6
Fuel economy	zero	15.6%	27.8%	32%

ever, the reused energy varies significantly with different energy management strategies. The optimal torque management strategy takes advantage of the supply oil pump, the design of front-wheel-drive configuration and the analysis of the main features extracted from DP optimization to improve the reuse rate and fuel economy. This provides a practical method for improving the fuel economy of a parallel hydraulic hybrid vehicle.

6. CONCLUSION

Because of the complexity of coordinating the work among the hydraulic hybrid vehicle components, it is difficult to establish an accurate mathematical model. Therefore, the based-rules control strategy is still the main method for the hydraulic hybrid vehicle. In this study, a new type of configuration for the parallel hydraulic hybrid vehicle is presented and the supply oil pump is introduced to minimize the disadvantages of hydraulic accumulator. An optimal energy management of hydraulic hybrid vehicle is formulated and solved by using DP algorithm to minimize the fuel consumption. A fuzzy-based optimal torque management strategy is built using the DP optimization results to distribute the torque between the engine and hydraulic pump/motor. A back-forward PHHV simulation model is established by Simulink, and the optimal torque management strategy is applied on PHHV to investigate the fuel economy. The simulation results show that the presented torque management strategy minimized the disadvantages of accumulator's lower energy density, reasonably distributed the propulsion energy between the two power sources, reduced the switching frequency of different work modes, and improved the fuel economy and adaptability of different working conditions, which provided a practical feasible method for improving fuel economy of the hydraulic hybrid vehicle.

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