Experimental Investigation of a Novel Dual-mode Power Split System for Passenger Vehicle

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Keywords: Hybrid electric vehicle, Power split, Planetary gear, Input-split, Compound-split.

Abstract: Hybrid systems are becoming ever more widely used because they can improve the fuel economy of automobiles. This paper proposes a new hybrid system based on the three row planetary gear train, which can switch between input-split and compound-split mode according to different road conditions. This paper introduces its structure and operating mode, and uses the 1.8L displacement Toyota Prius as an example. According to its design parameters, a prototype is designed and a control strategy based on logic threshold is established. The operating characteristics of the system were analyzed through a bench test. The experimental results show that compared with the 1.8L Toyota Prius power train, the novel dual-mode power split hybrid power train system can reduce fuel consumption by 11.4%.

1 INTRODUCTION

In the next 50 years, the world population will grow from 6 billion to 7 billion, and car ownership will increase from 700 million to 2.5 billion (chan, 2001). If all these cars continue to use engines, the consequent environmental pollution problems will be unimaginable (chan, 2002), and these factors force us to rapidly develop alternative energy-driven automotive technology. At present, hybrid technology is one effective way to improve fuel consumption and reduce emissions.

According to the definition, the hybrid electric vehicle needs to have two power sources of engine and electric motor, and can achieve high energy utilization rate through efficient and precise control system, which makes it have low fuel consumption, low emission and excellent advantages such as dynamic performance (Ehsani, 2007; Lin, 2003; Sciarretta, 2007 ; Pisu, 2007). According to the connection form of the internal combustion engine with the motor and the transmission, the hybrid electric vehicle can be divided into three types: a series hybrid vehicle (SHEV), a parallel hybrid vehicle (PHEV) and a series-parallel hybrid vehicle (SPHEV) (Meisel, 2006).

In the first generation of the Prius, Toyota creatively proposed the use of a planetary gear power-split system for hybrid vehicle (Meisel, 2011). The system consists mainly of an engine, a planetary gear train and two motors. Using the planetary gear train as a power coupling device, the decoupling of the engine rotating speed and torque can be realized by two motors and a planetary gear train with two degrees of freedom, and the power of the engine is divided into two parts: electric power and mechanical power. However, the power-split mode of this configuration is relatively simple, and it is not possible to switch modes to adapt to different road conditions (Miller, 2006 ; Liu, 2008).

The dual-mode hybrid system is a hot research problem in the field of hybrid technology because it has two power-split modes and can improve fuel economy in a wider range of transmission ratios. This paper proposes a novel dual-mode hybrid system. The Prius was used as an example to design a prototype. The control strategy based on the logic threshold was used to test the performance of the system. The experimental results show that the fuel economy of the novel dual-mode hybrid system is improved compared with the Toyota Prius powertrain.

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2 DESCRIPTION OF THE SYSTEM STRUCTURE AND OPERATING MODE

The novel dual-mode hybrid system proposed in this paper has two power-split modes: input-split and compound-split. The system works in the compound-split mode in the middle and low gear ratio range, and works in the input-split mode in the high gear ratio range. The mode is switched by the control of the clutches.

The configuration of the novel dual-mode power-split hybrid system proposed in this paper is shown in figure 1. The parameters of different parts of the system are shown in table 1.

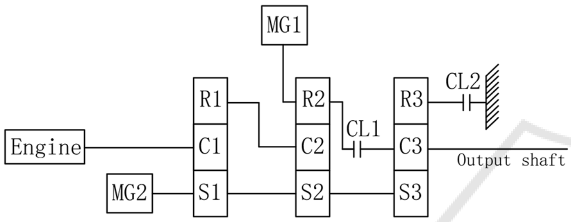


Figure 1: Configuration of the novel dual-mode power-split hybrid system.

Table 1. System parameters.

Component	Parameter	Value
Vehicle	Weight/kg	1467.4
	Wheelbase/mm	2700
	Wind resistance coefficient	0.29
	Tire radius/m	0.282
Engine	model	5ZR-FXE
	Maximum power/kW	73
	Maximum torque/Nm	142
	Displacement/L	1.8
MG1	MG1 rated power/kW	30
	MG1 rated speed/rpm	3000
MG2	MG2 rated power/kW	33
	MG2 rated speed/rpm	3000
Battery	capacity/kWh	1.3

The system has two types of power-split modes: input-split and compound-split. The corresponding vehicles have reverse gear, low speed running, medium and high speed running, rapid acceleration, braking and other working conditions. The control system selects different operating modes based on the power demand signal from the driver, the current vehicle speed, the battery SOC value, and the current operating state of the engine and the motors. According to the working state of the engine, MG1, MG2 and the engagement or disengagement of the CL1 and CL2, the system has a total of 10 operating modes, as showed in table 2.

Table 2: The operating modes of the system.

Operating mode	Engine	MG1	MG2	Engine and system	CL1	CL2
Reverse gear	stop	stop	run	disconnected	disengaged	engaged
Single motor drive	stop	stop	run	disconnected	disengaged	engaged
Dual motor drive	stop	run	run	disconnected	engaged	disengaged
Engine cold start	follow	run	stop	connected	disengaged	engaged
Engine hot start	follow	run	run	connected	disengaged	engaged
Charge	run	run	run /stop	connected	disengaged	engaged
Input-split	run	run	Run	connected	disengaged	engaged
Compound-split	run	run	run	connected	engaged	disengaged
Mild brake	stop	stop	run	disconnected	disengaged	engaged
Heavy braking	stop	run	run	disconnected	engaged	disengaged

3 CONTROL STRATEGY

Control strategies of existing power-split hybrid vehicle mainly include logic threshold-based control strategies, genetic algorithm based control strategies, fuzzy rule based control strategies, and adaptive dynamic control strategies (Salmasi, 2007; Sciarretta, 2007). In order to make it easier to be compared and analyze the experimental results, this paper chooses the control strategy based on logic threshold. The control strategy based on the logic threshold is essentially to map all the states that the vehicle may encounter during driving to different operating modes of the hybrid system, and at the same time, set the discriminating conditions and thresholds for the transition between different modes. For the novel dual-mode power-split hybrid system proposed in this paper, there is a total of 10 effective operating modes as showed in table 2. The control strategy based on the logic threshold needs to select the corresponding operating modes according to the set rules and determine the power distribution of the engine and the two motors.

The mode switching rules based on the logic threshold are as follows: The target operating point and the permissible working range of the engine are set according to the efficient operating range of the engine. Set the battery SOC value working range to ensure its performance and extend its service life. According to the current gear position information and torque demand collected by the sensors, combined with the battery SOC value, select the operating mode of the system. The heavy braking energy recovery mode or the mild braking energy recovery mode is selected according to the vehicle speed and the battery SOC. The threshold values of the main parameters are set as follows.

3.1 Battery SOC Value

The SOC (state of charge) value of expresss the power level of battery, which is usually represented by a number between 0 and 1. In the process of using the hybrid vehicle,as to prolong the service time of battery, it is necessary to shallowly charge it. Therefore, in the control strategy based on the logic threshold, the upper limit SOCmax=0.8 and the lower limit SOCmin=0.4 are respectively set. In any pattern, if the current SOC of battery is <SOCmin, the engine is started and enters the charging mode or the hybrid driving mode. When the vehicle needs to decelerate braking, according to the real-time SOC of battery, the proportion of electric brake participation during braking is determined; when SOC>SOCmax, the full hydraulic braking mode is adopted.

3.2 Vehicle Speed Threshold V_ref

Both the engine and the MG1 and MG2 have their maximum speed limits, and each has a speed range corresponding to the efficient working area. Therefore, different speed thresholds need to be set so that the vehicle always runs in the most suitable mode while driving. Set the vehicle speed threshold v_ref1=30km/h, v_ref2=60km/h. The engine is inefficient at idle speed. Therefore, when SOC value of the battery is greater than its lower limit value, the engine only run when the vehicle speed is greater than the threshold value v_ref1. When the vehicle speed is lower than v_ref1, it operates in pure electric mode. The input-split mode is suitable for low speed. Therefore, when the vehicle speed is in the range of (v_ref1, v_ref2), the input-split pattern is preferentially chosen; if the vehicle speed is greater than v_ref2, switch to compound-split mode.

3.3 Demand Torque T_req Threshold

When designing and optimizing a hybrid system, not only its fuel economy but also the dynamic performance of the vehicle must be met. The real-time torque required during vehicle travel is derived from the opening of the throttle and brake pedals and represents the instantaneous power demand. The control strategy of this paper linearly converts the signal of the accelerator pedal opening and the demand torque, and assigns it to the engine and two motors with the goal of fuel economy. While the engine, MG1 and MG2 have their upper limit of output torque and the optimal output torque range, so we should set the threshold for the demand torque as the evaluation standard for mode switching.

First,it is judged that it is currently in the drive mode, the parking mode or the braking mode according to $T\_req > 0, T\_req = 0$,or T_req< 0. In the drive pattern: if the battery SOC>SOCmin, the vehicle speed v<30km/h, the vehicle runs in pure electric drive mode. When $T\_req < 30Nm$, a single motor drive, when T_req>30Nm, double motor drive. When the instantaneous torque demand T_req>90 Nm, the engine starts to work and provides torque. When T_req=0 and the duration is greater than 3s, the vehicle enters the parking or coasting mode. At this time, if the battery SOC value is greater than the lower limit threshold, the engine stops. In the braking mode, the mechanical brake, single motor auxiliary electric brake or dual motor auxiliary electric brake mode is selected rely on the vehicle speed and battery SOC value.

3.4 Validation Test

Figure 2 is the model of the novel dual-mode power-split hybrid system, including MG1, three-row planetary gear train, engine input shaft and MG2 motor input shaft. In order to simplify the structure, the MG1 rotor is designed as a hollow structure, directly connected to the ring gear of the second planetary gear train. Considering the experimental verification of the hybrid system, the two clutches showed in figure 1 need to be equipped with hydraulic or electronic control units separately, which is difficult and costly. At the same time, the structure of the three sets of planetary rows is too complicated. Therefore, in the structural design and subsequent experimental research, the structure consisting of two sets of planetary rows with dual output ports is used, and the reduction ratio of the third row of planetary transmissions is realized by the sprocket. During system testing, the current operating mode can be selected as input-split or compound-split through different output port.

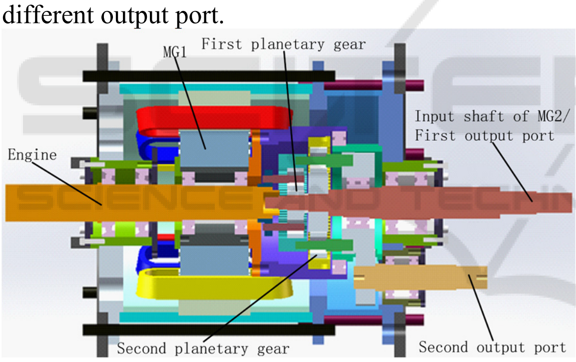


Figure 2: The 3D model of the novel dual-mode power-split hybrid system.

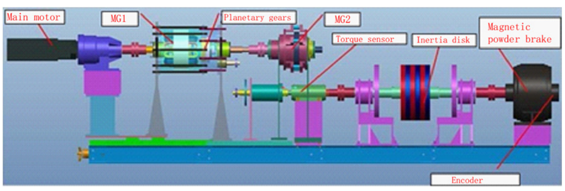


Figure 3: The model of the hybrid system test bench.

In order to test the speed and torque of each component of the hybrid system under different working modes and to test the fuel economy of the system, the experimental platform of the hybrid system is built according to figure 3. The physical diagram is shown in figure 4. It includes a main motor for simulating the engine, an experimental device, a torque sensor for testing the output speed and torque signal, an adjustable inertia disk for simulating the vehicle's driving inertia, and a magnetic powder brake. The hybrid system includes a flux switching permanent motor(FSPM) as MG1,a permanent magnet synchronous motor(PMSM) as MG2, and a power split device composed of two rows of planetary gear trains that are connected to the subsequent test unit through a sprocket of the first or the second output port. The control system mainly consists of three servo motor drivers, two upper computers and one motion control card. The upper computer connected to the control card sends the speed and torque control commands to the servo motor driver by means of the motion control card, and reads the current and speed signals collected by the driver. The industrial computer is used to control the magnetic powder brake, and read the speed and torque signals measured by the torque sensor.

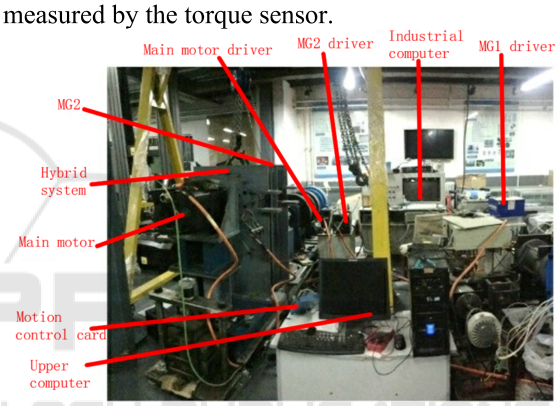


Figure 4: Hybrid system test bench.

In order to verify the performance of the novel dual-mode power-split hybrid system, the fuel economy experiment was carried out on the system. The fuel economy experiment was carried out under the NEDC cycle condition (Wang, 2013).The target and actual vehicle speed in the experimental process are shown in figure 5. It can be seen from the figure that the presence of the motor effectively improves the acceleration and deceleration performance of the hybrid system, so the actual vehicle speed and the target speed basically coincide.

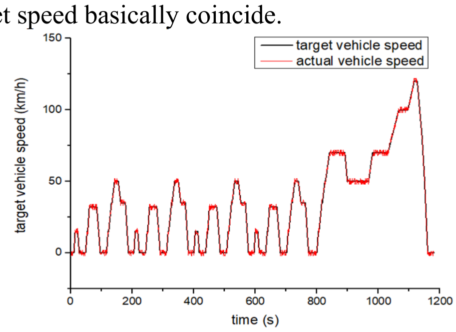
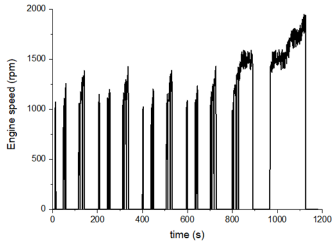
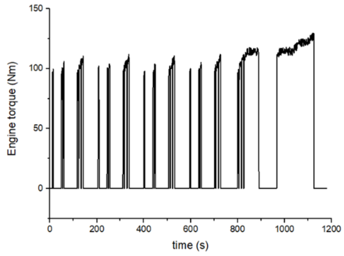


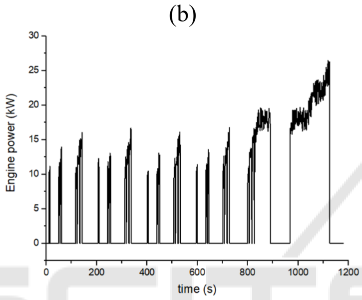
Figure 5: Comparison of target speed and actual speed.



(a)



(b)

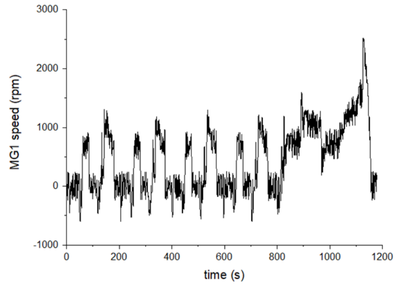


(c)

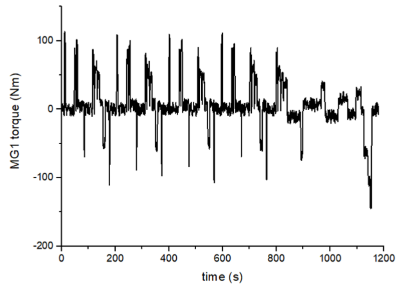
Figure 6: The speed, torque and power of the engine:(a) variation of engine speed with time;(b) variation of engine torque with time;(c) variation of engine power with time.

The engine speed, torque and power during the experiment is shown in figure 6. As we can see from figure 6(a), since there are two motors in the hybrid system, the vehicle is mainly driven by the motor at low speed. Under normal urban conditions, the engine does not work most of the time, and only starts charging the battery when the battery SOC value is low.

In order to analyze the performance of the two motors, the curves of the speed and torque of the two motors are obtained during the experiment. As is shown in figure 7, in low speed case (less than 30km/h), MG1 does not work and torque of it is 0 Nm. In this case, MG2 is used as the drive motor. In the case of medium speed, when the battery SOC is greater than 0.4, MG1 and MG2 drive the vehicle together. When the battery SOC is less than 0.4, the engine is started. At this time, the engine speed and torque are adjusted by MG1 and MG2, so that the engine always works in high efficiency.



(a)



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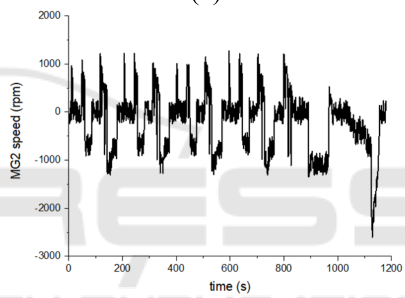

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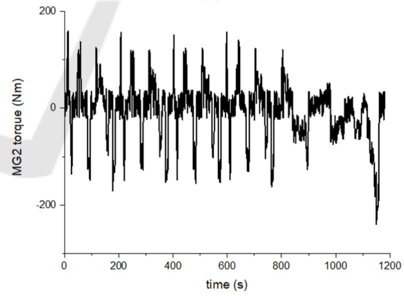
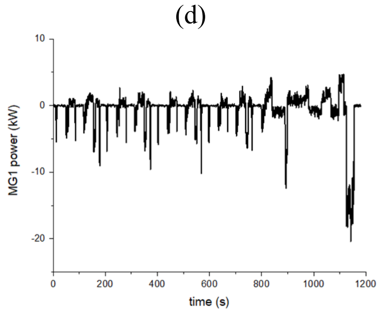
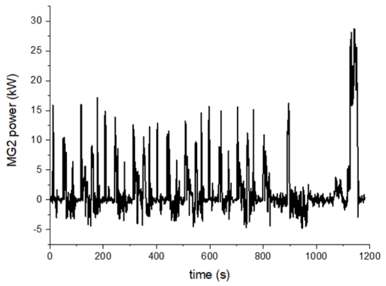


(d)



(e)



(f)

Figure 7: The speed, torque and power of two motors: (a)variation of MG1 speed with time; (b) variation of MG1 torque with time; (c) variation of MG2 speed with time; (d) variation of MG2 torque with time; (e) variation of MG1 power with time; (f) variation of MG1 power with time.

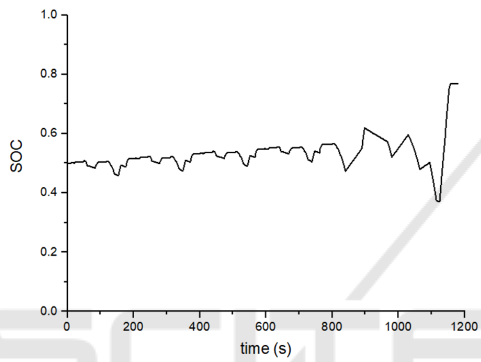


Figure 8: The SOC value of battery.

Limited by the experimental conditions, the battery is replaced by a simulation model. According to the measured power of the engine, MG1, and MG2, theoretical SOC of the battery can be calculated, and the variation curve is shown in figure 8. In pure electric mode, the energy of the motor is provided by the battery, the SOC value decreases, and when the vehicle speed increases, the system is in the engine drive mode. If the SOC value is lower at this time, part of the energy of the engine is used to drive the car, and the other part is used to charge the battery to increase the SOC of the battery. When the system is in a braking state, braking energy is recovered by MG1 and MG2 and stored in the battery.

In order to evaluate the fuel economy of the proposed novel dual-mode power-split hybrid system, the equivalent fuel consumption of the Prius hybrid system and the novel dual-mode power-split hybrid system is compared under the same driving cycle. As showed in table 3, the novel dual-mode power-split hybrid system can save fuel consumption by 11.4% compared to the Prius hybrid system. It can be seen that the novel dual-mode power-split hybrid system can effectively improve fuel economy.

Table 3. Comparison of fuel consumption rate.

	Fuel consumption(L/100km)	Energy saving rate
Prius	4.3	
Novel dual-mode power-split hybrid system	3.81	11.4%

5 CONCLUSION

This paper proposes a novel dual-mode power-split hybrid system based on a three-row planetary gear train, which is mainly composed of an engine, a three-row planetary gear train and two motors. After analyzing the configuration and operating mode of the system, taking the Toyota Prius as an example, a prototype was made and a bench test was carried out. The experimental results show that the fuel economy of the novel dual-mode power-split hybrid system is 11.4% higher than the Toyota Prius. It can be seen that the novel dual-mode power-split hybrid system is a good hybrid solution.

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REFERENCES

Chan C, Chau K. (2001). Modern Electric Vehicle Technology[J]. *Power Engineer*, 16(5):**240-240**.

Chan C C. (2002). The state of the art of electric and hybrid vehicles[J]. *Proceedings of the IEEE*, 90(2):**247-275**.

M. Ehsani, Y. Gao, and J. Miller. (2007). “Hybrid electric vehicles: Architecture and motor drives,” *Proc. IEEE*, vol. 95, no. 4, pp. 719–728.

C. C. Lin, H. Peng, J. W. Grizzle, and J. Kang. (2003). “Power management strategy for a parallel hybrid electric truck,” *IEEE Trans. Control Syst.Technol.*, vol. 11, no. 6, pp. 839–849.

A. Sciarretta and L. Guzzella. (2007). “Control of hybrid electric vehicles,” *IEEE Control. Syst. Mag.*, vol. 27, no. 2, pp. 60–70.

P. Pisu and G. Rizzoni. (2007). “A comparative study of supervisory control strategies for hybrid electric vehicles," *IEEE Trans. Control Syst. Technol.*, vol. 15, no. 3, pp. 506–518.

Meisel J. (2006). An Analytic Foundation for the Toyota Prius THS-II Powertrain with a Comparison to a Strong Parallel Hybrid-Electric Powertrain[C]// SAE 2006 World Congress & Exhibition.

Meisel J. (2011). Kinematic Study of the GM Front-Wheel Drive Two-Mode Transmission and the Toyota Hybrid System THS-II Transmission[J]. *Sae International Journal of Engines,* 4(1):1020-1034.

Miller, J.M. (2006). Hybrid electric vehicle propulsion system architectures of the e-CVT type. *IEEE Trans. Power Electron*. 21, 756–767.

Liu, J.; Peng, H. (2008). Modeling and control of a power-split hybrid vehicle. *IEEE Trans. Control Syst. Technol*. 16, 1242–1251.

Salmasi, F.R. (2007). Control strategies for hybrid electric vehicles: Evolution, classification, comparison, and future trends. *IEEE Trans. Veh. Technol*. 56, 2393–2404.

Sciarretta, A.; Guzzella, L. (2007). 2007 Control of hybrid electric vehicles. *IEEE Control Syst*. 27, 60–70.

J. Wang, X. Yuan, and K. Atallah. (2013). 2013 Design optimization of a surfacemounted permanent-magnetmotor with concentrated windings for electric vehicle applications, *IEEE Trans. Veh. Technol.*, vol. 62, no. 3, pp. 1053–1064.