Matching and Optimization for Powertrain System of Parallel Hybrid Electric Vehicle

Gao Jianping[1,a], Wei Yuehui[1,b], Liu Zhennan[1,c], Qiao Hongbing[1,d]

[1] Vehicle & Motive Power Engineering College, Henan University of Science & Technology, 48 Xiyuan Road, Jianxi District, Luoyang, China

[a]gjpcar@gmail.com,[b]weigaosun@163.com,[c]liukhev@126.com,liu_liuk@163.com

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Abstract. The parameters matching of the hybrid powertrain system of the hybrid electric vehicle has a directly impact on the performance of the vehicle dynamic and the fuel economy. The preliminary match of the powertrain system base on analysis of Driving Cycle is done, then the software of AVL-Cruise and Matlab are integrated with Isight to optimize parameters of match, by using the Multi-Island GA and NLPQL to establish the combinatorial optimization algorithm. The results show that the fuel economy have been improved by 10.92% without sacrificing the dynamic performance and under the premise of ensuring the limits of the state of charge of battery.

Introduction

The hybrid electrical vehicle consists of two or more different power sources, which improves fuel consumption and emission without sacrificing the dynamic performance of the vehicle. The highly efficient operation of the multi-energy powertrain system firstly is dependent on reasonable matching, then optimization of the parameters is the key to further improve the performance of vehicle.

The parameter matching of the hybrid powertrain system has been done by traditional matching method of the automotive theory[1,2,3], which only meets the analysis of the characteristic conditions, and does not consider the typical driving cycle. The matching based on analysis of the driving cycle meets the requirements of the characteristic conditions and the typical driving cycle, except the working conditions adaptability[4].

The orthogonal experimental design optimization method is introduced in matching of the hybrid powertrain system[5,6,7], however, the comparison of only some limited parameters combinations be done, the fuel economy is not optimal. The parameters optimization of the hybrid powertrain system with the genetic algorithm and the adaptive hybrid genetic algorithm belongs to the global exploration method which lacks ability of the local optimization[8,9]. The optimization of the direct method for the hybrid powertrain system is not the highly accuracy, and slow search for the high-dimensional problem[10,11].

This paper presents matching and optimization of a parallel hybrid vehicle powertrain system. The preliminary match will be done based on analysis of *the characteristic conditions*, *the typical driving cycle* and *the working conditions adaptability*, the software of AVL-Cruise and Matlab are integrated with Isight to optimize parameters of matching for the best fuel economy, by using the Multi-Island GA and the NLPQL to establish *the combinatorial optimization algorithm* for improving the global and local search ability.

Configuration of Hybrid Powertrain System

The hybrid powertrain system of the single-axis parallel hybrid vehicle has the advantages of the simple structure, easy to implement, the high efficiency for transmission and the flexible operating modes. The structure is shown in Fig. 1, the overall parameters are listed in Table 1.

The idle stop-start mode and the pure motor driving mode can be realized by the dual clutch increased in motor the front and rear, in addition, there are the pure engine driving mode, the

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driving charge mode, the hybrid driving mode, the coast feedback mode and the brake feedback mode.

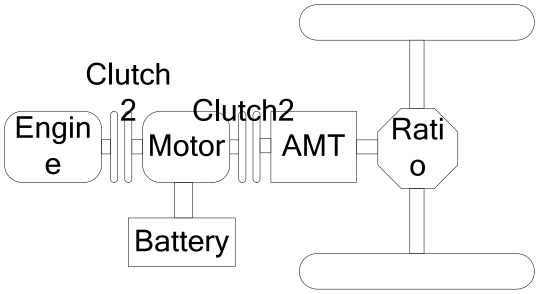

Fig. 1 Configuration of the hybrid powertrain system of the single-axis parallel hybrid electric vehicle

Table 1 Overall parameters of the single-axis parallel hybrid electric vehicle

Parameter	Value	Parameter	Value
Curb mass m_a [kg]	12600	Rolling resistance coefficient f	0.013
Total mass m [kg]	18500	Driveline efficiency η_T	0.93
Front area A [m^2]	6.6	Tire static radius r_a [mm]	452
Air drag coefficient C_D	0.55	Tire dynamic radius r_d [mm]	473

Parameters Matching of Hybrid Powertrain System

The parameters match of the hybrid electric vehicle must be done on the basis of the analysis of the design indexes that consist of the typical driving cycle, the characteristic conditions, the working conditions adaptability. They are listed in Table 2.

Table 2 Design indexes of the single-axis parallel hybrid electric vehicle

Condition	Description	Requirement
Characteristic conditions	Maximum velocity [km/h]	≥80
	Acceleration time from 0 to 50 km/h [s]	≤20
	Climbing gradient at 15 km/h [%]	≥12
Typical driving cycle	Path tracking absolute error of the typical urban bus driving cycle in china [km/h]	≤3
Working conditions adaptability	Pure motor driving distance at 10km/h and on slope gradient of 7% [km]	≥1
	Acceleration time from 0 to 18 km/h [s]	≤5
	Constant velocity driving distance at 40km/h and on slope gradient of 4% [km]	≥100
Rate of fuel saving	Rate of fuel saving of the driving cycle [%]	≥30

The parameters matching of the hybrid powertrian system mainly focuses on the total power of the powertrain, the engine, the driving motor, the battery, the transmission and the ratio.

2.1 Total Power of the Powertrain. The total power of the powertrain that need to meet all of the indicators of the dynamic which contain the typical driving cycle, the characteristic conditions and the working conditions adaptability can be gotten by the following Eq. 1.

$$P \geq \max(P_{v_{\max}}, P_{acc}, P_{i\_max}, P_{i\_l}, P_{cycle}) + P_{aux}. \quad (1)$$

where, P is the maximum total power, $P_{v_{\max}}$ is the power demand to maintain the maximum velocity, P_{acc} is the power demand of acceleration performance of the characteristic conditions, P_{i_max} is the power demand to maintain the maximum climbing, P_{i_l} is the power requirement of the vehicle at the middle constant velocity on the hillside path of the working conditions adaptability, P_{cycle} is the power demand of the typical driving cycle, P_{aux} is the accessory power.

The power requirements of the typical driving cycle, the characteristic conditions and the working conditions adaptability can be obtained by the power balance Eq. 2.

$$P=1/(3600\eta_T)\times(mgf\cos\alpha + mg\sin\alpha + C_D A\, v^2/21.15 + m\delta\frac{dv}{dt})\, v. \tag{2}$$

where, g is the acceleration of gravity, dv/dt is the acceleration, i is the climbing inclination, α is the road surface slope, α=arctan i. v is the velocity, δ is the equivalent conversion coefficient of the vehicle rotating mass.

2.2 Engine Parameters Matching. Engine is the core and main power source of the powertrain system for the hybrid electric vehicle designed in this paper, the power requirement of engine need to meet the conditions in the following which is defined by the Eq. 3.

(1) Power demand of driving at cruising velocity.

(2) The average of driving power requirement for the typical cycle conditions.

(3) Power requirement of engine driving mode at constant velocity on the hillside path of the specified slop for the conditions adaptability.

$$P_e \geq \max(P_{v_{cruise}},\ P_{cyc\_ave},\ P_{i\_l}) + P_{aux}. \tag{3}$$

where, P_e is the maximum power of the engine, $P_{v_{cruise}}$ is the power demand of the vehicle at cruising velocity, P_{cyc_ave} is the average of power requirement for the typical cycle conditions, P_{i_l} is the power requirement of the vehicle at the middle constant velocity on the hillside path of the working conditions adaptability.

2.3 Motor Parameters Matching. The function of motor is the peak shaving and valley filling for the power of the vehicle, which cancels the engine idling and realizes pure electric starting at the lower velocity or the lower-load operation, and can realize regenerative feedback energy. Its power requirements are described because of the following facts. We can get the motor power by Eqs. 4.

(1) Rated motor power meets the power requirement of pure motor driving at the low-velocity for the conditions adaptability.

(2) Peak motor power meets acceleration time requirement of the motor or the power requirement of the low-speed pure motor driving for the condition adaptability, and can start the engine.

(3) The sum of the rated motor power and engine power should be greater than the maximum driving power demand.

$$P_m \geq P_i.$$
$$P_{m\_peak} \geq P_i + P_{eng\_st}.$$
$$P_{m\_peak} \geq P_{acc}(t) + P_{eng\_st}.$$
$$P_{m\_peak} \geq P(t) + P_e. \tag{4}$$

where, P_m is the rated motor power, P_{m_peak} is the peak motor power, P_i is the power requirement of low-speed pure motor driving of the working conditions adaptability, P_{eng_st} is the engine starting power, $P(t)$ is the power of the driving cycle.

2.4 Battery Parameters Matching. Energy requirement of the battery packs is mainly decided by the continuous acceleration performance and the pure electric driving range from the working conditions adaptability, and need to satisfy the conditions in the following. It is gained by Eqs. 5.

(1) The output power of the battery is greater than the minimum power of the motor peak power from the Eqs. 4.

(2) The capacity of the battery meets the energy demand of the continuous pure electric driving mileage.

(3) The capacity of the battery should be greater than the energy requirement of the continuous acceleration boost from motor.

$$P_{b\_max} \geq P_{m\_peak}/(\eta_b\eta_m).$$
$$C \geq \max(Q_a, Q_i)/[(SOC_L - SOC_H)\, U_b\, \eta_b\, \eta_m]. \tag{5}$$

where, P_{b_max} is the maximum power of the battery, η_b, η_m is the average efficiency of the battery and the motor, Q_a, Q_i are the electric energy demand of continuous acceleration driving and the pure electric driving mileage, SOC_L, SOC_H are the upper and lower limit of the state of charge for battery, U_b is the working voltage of the battery, C is the capacity of the battery.

2.5 Parameters Matching of Transmission. The ratio matching mainly considers the maximum and minimum transmission ratio of driveline which is determined by the maximum velocity and the maximum climbing gradient of the characteristic conditions.

The vehicle is driving at the maximum velocity, corresponding to the minimum transmission ratio at top gear of driveline, and the engine should have a back-up power. At this time the minimum transmission ratio is got by the following the Eq. 6.

$$0.377\ n_{ep}r_d/v_{max} \le i_{t\_min} \le 0.377\ n_{max}r_d/v_{max}. \quad (6)$$

where, i_{t_min} is the minimum ratio of the driveline is the single ratio which is i_0, n_{max} is the maximum engine speed, n_{ep} is the speed of the engine rated power.

When the vehicle is driving at the maximum climbing gradient, corresponding to the lowest gear, the following Eq. 7 is the condition of the maximum transmission ratio at the lowest gear.

$$i_{t\_max} \ge mg(f \cos \alpha_{max} + \sin \alpha_{max})\ r_d/(T_{max}\eta_m). \quad (7)$$

where, i_{t_max} is the maximum ratio of driveline, T_{max} is the maximum torque of motor.

The deflection geometric progression growth method is adopted in middle transmission parameter distribution.

According to overall parameters of the vehicle in Table 1, the condition Analysis and the design indicators in Table 2, the main parameters of the hybrid powertrain system for the single-axis parallel hybrid electric vehicle have been calculated by the above Eq.1 – Eq. 7 which are shown in Table 3.

Table 3 Parameters of the hybrid powertrain system

	Parameter	Number value	Parameter	Number value
Engine	Engine type	4-cylinder diesel engine	Maximum torque [N·m]	655
	Maximum power [kw]	132	Maximum speed [r/min]	2500
Motor	Rated power [kw]	50	Rated torque [N·m]	340
	Rated speed [r/min]	1450	Speed ratio	2
Battery	Rated voltage [V]	358	Capacity [Ah]	60
Driveline	Transmission type	4 shift AMT	Ratio of each gear	4.65,2.64,1.59,1.0
	Final drive ratio	4.88		

Parameters Optimization of the Hybrid Powertrain System

The preliminary parameters matching of the hybrid powertrain system has a directly impact on the various performance of the vehicle, it is necessary to optimize the parameters in order to achieve the optimum fuel efficiency.

The aim of the designing of hybrid electric vehicle is to reduce the fuel consumption and pollutant without sacrificing the dynamic performance. So the purpose of the study is to choose several possible sizes of components for the given powertrain configuration, given the control strategy and specific driving cycle. This leads to the solution of a constrained nonlinear programming problem as described by Eqs. 8.

$$\begin{aligned} &\min \quad f(X). \\ &s.t. \quad g_i(X) \ge 0 \quad j=1,2,\ldots,m. \\ &\qquad x_i^l \le x_i \le x_i^u \quad i=1,2,\ldots,n. \end{aligned} \quad (8)$$

where, $f(X)$ is the objective function, $g_i(X)$ is the nolinear function that describe the design constrain, m is the number of constrain function, x_i is the variable parameter optimized, n is the number of variable optimized, x_i^l, x_i^u is the upper and lower limit of the optimization parameter.

3.1 Optimization Objective. The design target of hybrid electric city bus is to achieve optimal fuel economy and the lowest emissions on the condition of the dynamic performance premised.

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The optimization objective include the engine fuel consumption and the motor electric consumption for the hybrid electric bus in the paper whose the emissions is not considered. They are transformed to the one by literature[12] which is the combined fuel consumption per 100 kilometers of driving cycle, it is expressed by Eq. 9.

$$f\ (X)=Q. \tag{9}$$

where, Q is the fuel consumption per 100 kilometers of the driving cycle.

3.2 Optimization Parameters. As previously mentioned, we select the matching parameters of optimization which have a significant impact on the performance of the vehicle, the optimization variables selected are shown in Table 4.

The hybrid electric vehicle is designed by changing the original ICE vehicle, so the upper limit value of engine power is the average power of the original ICE vehicle that accelerates from standstill to maximum velocity, the lower limit value of engine power is gained by the minimum value of the Eq. 3. The upper limit value of the motor rated power is got by the maximum degree of hybridization of the power-assisted hybrid electric vehicle [13], the lower can be obtained the Eqs. 4. We can respectively select the upper and lower limits of the capacity of the battery from the power demand of the maximum climbing gradient and the minimum motor peak power obtained by the Eqs. 4. The limit values of final drive are got the Eq. 6.

Table 4 Optimization parameters

Parameters	Description	Lower limit value	Upper limit value
P_e	Maximum power of the engine [kw]	110	147
P_m	Rated power of the motor [kw]	40	80
C	Capacity of battery [Ah]	60	70
i_0	Ratio of the final drive	4.68	5.57

3.3 Constraint Condition. The constraint conditions of the parameters matching of hybrid electric vehicle are the upper and lower limits value of SOC of battery in Eq. 5 and the various indicators of the dynamic performance which are the maximum velocity, two acceleration time, the maximum climbing gradient and path tracking absolute error, and they are shown in Table 2.

3.4 Optimization Algorithm. The current optimization algorithms can be divided into the numerical optimization algorithm and the exploratory optimization algorithm, the former can quickly find local minima, but it is not good at the global optimization, the latter can find the global optimal area but it is less efficient and the poor for local optimization. So we make use of the respective advantages of the both to establish the combinatorial optimization algorithm which is a global-Local optimization algorithm composed of the Multi-island GA and the NLPQL.

We apply the AVL-Cruise to establish the simulation model of the hybrid electric vehicle and make Simulink build the control strategy, the simulation is ran through the interface module. The AVL-Cruise and Matlab are integrated in the Isight environment to run automatically. The flow chart of the optimization model is shown in Fig. 2.

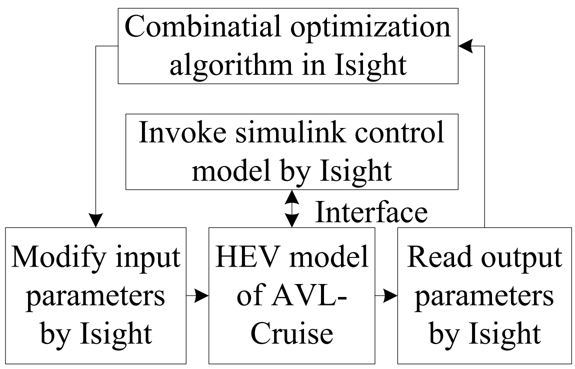


Fig. 2 Flowing chart of optimization integrated in Isight

3.5 Simulation Results and Analysis. Iterative process of the combined fuel consumption is displayed in the following Fig.3, the combined fuel consumption is decreasing with the iterative number increasing. The fluctuations frequently occurs, although the combined fuel consumption is gradually converge, which describe the stronger global search capability of MIGA. Iteration after 500 generations can show the local search capability of NLPQL.

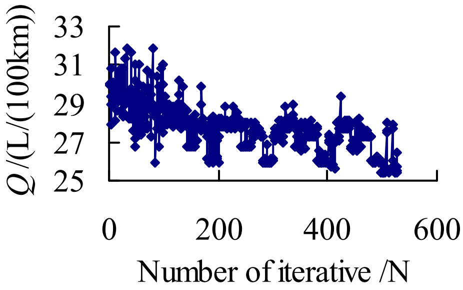


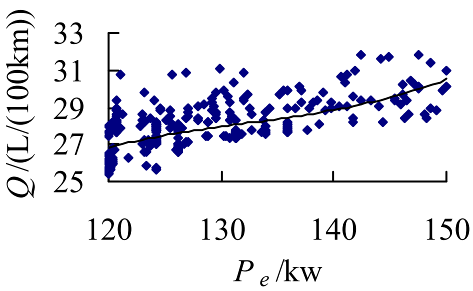
Fig. 3 Iterative process of the combined fuel consumption optimized

The comparison of the design variables and the optimization target for the before and after optimization are listed in Table 5. It can been seen that the minor engine power, the slight variations of motor power, the higher capacity of battery and the lager ratio of final drive are here. The combined fuel consumption of the driving cycle reduces by 6.76% than before optimization.

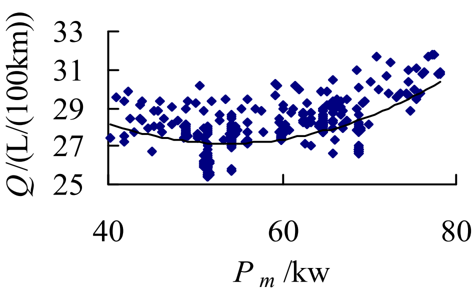
Table 5 Comparison of the optimization results

Optimization variable	Optimization before	Optimization after
Engine power P_e [kw]	132	120
Motor rated power P_m [kw]	50	52
Ratio of final drive i_0	4.88	5.37
Capacity of battery C [%]	60	65
Combined fuel consumption [L/(100km)]	28.56	26.63

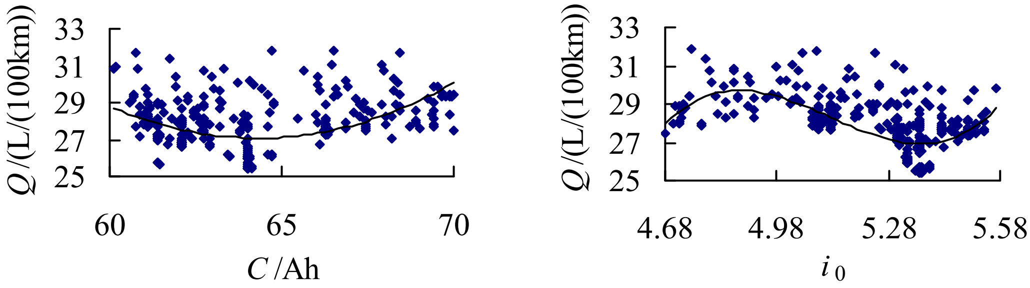
The distribution of the combined fuel consumption with the various parameters optimized is shown in Fig.4, and it draws the trend lines. It can be seen that the combined fuel consumption and the engine power is approximately linear relationship from Fig.4 (a), and approximate quadratic polynomial relationship of the combined fuel consumption and the motor power or capacity of power battery can be seen from Fig.4 (b) and Fig.4 (c), the relationship of combined consumption and the ratio of final drive can be seen from Fig.4 (d) to approximate cubic polynomial relationship. The minimum value area of the combined fuel consumption corresponds to the parameters area optimized, which not only prove that the optimization has certain validity, but also it is illustrated that the combinatorial optimization algorithm has strong global and local search capabilities. The trend of the trend line in figures has a strong reference value to the power-assisted hybrid electric vehicle and has a certain reference significance to match of electromechanical coupling dynamic system of hybrid electric vehicles.



(a)



(b)



(c) **(d)**

Fig. 4 Relationship of combined fuel consumption and the parameters optimized
(a) Relationship of combined fuel consumption and engine power
(b) Relationship of combined fuel consumption and motor rated power
(c) Relationship of combined fuel consumption and capacity of battery
(d) Relationship of combined fuel consumption and ratio of final drive

The various parts parameters of the vehicle after matching and optimization are listed in Table 6. We select the same type engine on the market, considering to the credibility of comparison. Compared to the theoretical optimized value, engine power is a slight decrease. Motor and gearbox are the same with the initial matching program, the capacity of battery and the ratio of final drive use the theoretical value after optimization.

Table 6 Parameters of hybrid powertrain system after optimization

	Parameter	Number value	Parameter	Number value
Engine	Engine type	4-cylinder diesel engine	Maximum torque [N·m]	600
	Maximum power [kw]	118	Maximum speed [r/min]	2500
Motor	Rated power [kw]	50	Rated torque [N·m]	340
	Rated speed [r/min]	1450	Speed ratio	2
Battery	Rated voltage [V]	358	Capacity [Ah]	65
Driveline	Transmission type	4 shift AMT	ratio of each gear	4.65,2.64,1.59,1.0
	Final drive ratio	5.37		

The performance of the vehicle after optimization and match again is listed in Table 7. It can be seen that the dynamic performance is much better than the design index, acceleration time from standstill to 50 km/h cut down by 3s than the design index, the path tracking absolute error for the driving cycle is little, the range of pure electric driving meets the design requirement. The combined fuel consumption reduces by 4.47% than the theoretical value after optimization, cut down by 10.92% than the initial match and drop by 39.14% than the original ICE vehicle(the fuel consumption is 41.8 L/(100km)).

Table 7 Performance of the single-axis parallel hybrid electric vehicle after optimization

Description		Value
Characteristic conditions	Maximum velocity [km/h]	89.31
	15km/h climbing gradient [%]	12.19
	Acceleration time from 0 to 50 km/h [s]	17.06
Driving cycle	Path tracking absolute error [km/h]	2.17
Working conditions adaptability	Acceleration time from 0 to 18km/h [s]	4.12
	Pure electric driving distance at 10km/h and on the slope of 7% [km]	1.67
Electric consumption	Electric consumption of the driving cycle [kwh/(100km)]	7.21
Fuel consumption	Fuel consumption of the driving cycle [L/(100km)]	23.05
Combined fuel consumption	Combined fuel consumption of the driving cycle [L/(100km)]	25.44

Rate of fuel saving	Rate of fuel saving of the driving cycle [%]	39.14

Conclusions

According to the analysis of the characteristic conditions, the conditions adaptability and the driving cycle, the parameters matching for the hybrid powertrain system of the hybrid electric are done. For improving fuel economy and ensuring the best matching performance, we use the combinatorial optimization algorithm composed of the multi-island GA and the NLPQL to optimize the power of engine and motor, the capacity of battery and the ratio of the final drive.

The results of optimization is that the fuel economy has been improved by 6.76% than the before optimization without sacrificing the dynamic performance and under the premise of ensuring the limits of the state of charge of battery, it is shown that the combinatorial optimization algorithm has a stronger searching ability for the global and local optimization. The matching parameters of the components greatly effect on the fuel economy, so it is necessary to optimize for the best fuel economy.

The dynamic performance after matching and optimization for the hybrid electric vehicle is much better than the design indexes, the acceleration performance is very good, the path tracking absolute error for driving cycle is little, the range of pure electric driving meets the design requirement. The combined fuel consumption reduces by 4.47% than the theoretical value after optimization, cut down by 10.92% than the initial match and drop by 39.14% than the original ICE vehicle, and it is better than the design index.

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