Parameters and control optimisation of hybrid vehicle based on simulation model

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Abstract: It is generally difficult to obtain accurate optimisation functions during parameters matching and optimisation process of the hybrid system, especially in the optimisation variable field containing both a continuous set and a discontinuous set and when the control strategy has an important influence on the system performance. To aim at the fuel economy of the parallel hybrid system, a global parameter matching and control strategies optimisation based on simulation model were proposed. The AMESim simulation model as the judgment module of the optimisation algorithm was used to match and optimise the main parameters and control strategies in the hybrid system. The communication of underlying parameters was developed by the VBA in EXCEL platform. Parameters match was implemented on a truck crane chassis in practice. The test results indicated that the rate of fuel saving reached 15.2%, which was generally consistent with the theoretical analysis. The parameters were met the energy-saving requirements of hybrid vehicles.

1 Foreword
Hybrid technology is the most feasible vehicle energy-saving technology at present. Due to the need to add other energy conversion devices on the power system, the weight of the whole vehicle is increased to a certain extent, and the original power system is disturbed. Therefore, the study on parameters matching and control strategy of hybrid vehicles is the core and the most important issue [1, 2].

The traditional method of parameters matching is mainly divided into two categories: one is the empirical power matching method used in engineering and the other is the function optimisation matching algorithm based on mathematical model. The former calculation method is relatively simple, taking the program that calculates sequentially and returns to do an amendment [3]. However, according to the extremum features of the mathematical function, the latter makes the function converge to the extremum using some general optimisation algorithms and modifying the parameters in the function with the target constantly.

As a result of the pursuit of modern control system performance, the traditional power matching method can only meet the power demand, and it is difficult to meet the needs of system optimisation. For that, many scholars begin to pay attention to the application of various general optimisation algorithms or combination optimisation algorithms to system matching [4, 5]. However, the mathematical optimisation method has great limitations in practical applications. First of all, the impact of the main parameters on the system performance of hybrid vehicles is difficult to express by accurate mathematical function; second, the effects of control strategies on the performance of hybrid vehicle are also great, and it interacts with the system parameters and restricts each other; and third, the calculation method of mathematical function extremum is based on the continuity of the function, but the component specifications used in hybrid vehicles are discrete, and the optimisation results are difficult to apply.

The global parameters matching and control strategy optimisation algorithm based on simulation model are adopted in this paper; that is, the main parameters are input in the form of matrix by VBA EXCEL, taking simulation model as the judgment module and the vehicle fuel economy as the goal, and synthesising the influence of the whole model planning parameters reasonably. The rationality of the optimisation algorithm is verified by the dynamic characteristics of the parameters.

2 Establishment of parallel hybrid dynamic simulation platform
Parallel hybrid is the most common hybrid configuration at present. In heavy vehicles, due to the large demand of driving and braking torque, the hydraulic secondary components of the normal parallel-type configuration require large displacement while the rated speed is low, which is not conducive to work within the full-speed range.

Therefore, the pre-positive gearbox of parallel configuration is used in this study. The braking and driving effect of the secondary components can be enlarged by using the speed ratio of the gearbox, and the speed range of the two components is fixed with the engine speed, while the engine speed is just matching the high-efficient working range of the secondary components. The schematic diagram is shown in Fig. 1. In driving condition, the driving power of the engine and the hydraulic secondary components (in the motor condition) enter the driving axle through the torque coupler and the gearbox. In braking condition, the kinetic energy of the vehicle is converted into hydraulic energy by using a hydraulic secondary component (in the pump condition) and stored in an accumulator through the torque coupler and the gearbox.

The VBA EXCEL receives the direct input vehicle status parameters and the main parameters of the hybrid system input by the MATLAB module simultaneously as the bottom communication to realise data interaction. The segment is shown in Excel worksheets and macros based on VBA [6, 7]. The input of data stream uses MATLAB software to input the design variables into the simulation model in matrix mode, and at the same time, the range of design variables is limited. VBA EXCEL enters data into the AMESim simulation model through a data communication interface and executes and feedbacks macro instructions in a simulation environment. The AMESim software simulates the design variables through batch processing and executes the judgment module function by reading and writing the correspondence file of the corresponding AMESim model. It can output simulation curve, return the simulation result to VBA EXCEL, and output the optimisation result file (Fig. 2).

3 Design variables constraints
As the hybrid system involves many parameters, this study takes main parameters influencing the efficiency larger as the design...
The design variables are constrained according to the design criteria where speed, and a normal speed: variables [8, 9]. The design variables include engine power, and the actual demand of the vehicle.

The gas pre-charge pressure of accumulator: The minimum working pressure of the hydraulic accumulator shall meet the minimum braking deceleration demand of the vehicle, and the maximum working pressure shall not be higher than the allowable working pressure of the components of the hydraulic system. At the same time, it should meet the design criteria of the general accumulator.

\[ p_{\text{max}} \leq \frac{2m\text{dv/dt}r}{b\rho h_i g V_{\text{max}}} \]

where \( i_p \) is the torque coupler drive ratio; \( r \) is the wheel radius, \( m; \) \( V_{\text{max}} \) is the maximum displacement of the hydraulic pump/motor, mL/r.

Design variable data stream uses MATLAB software interfacing with EXCEL VBA to realise data interaction. The EXCEL VBA calls the MATLAB software through the EXCEL link to constrain the design variables and then passes the resulting matrix to the EXCEL VBA variable for subsequent macro compilation The EXCEL VBA and AMESim interface sets and changes vehicle parameters using.param parameters communicate files. Communication between output variables is carried out through the.var file. At the same time, the required parameters of the AMESim are transferred as global variables using the.gp file, and the business execution and feedback of the macro instructions in the AMESim simulation environment are carried out. In the AMESim simulation environment, the operation and feedback of the macro instructions are carried out and the simulation results are stored in the data and xlsx files, so that the data interaction between the macro instruction function and the AMESim simulation model is realised.

4 AMESim simulation model

AMESim simulation is the core of the optimisation method, which is the judgment module of vehicle parameters and control optimisation. According to the principle of vehicle, the simulation model of the whole vehicle of hybrid vehicles is built by AMESim. The simulation model consists of vehicle driving module, power coupling module, gearbox module, hydraulic system module, engine module, and vehicle control module.

4.1 Vehicle driving module

The vehicle-driving module is mainly used to simulate the driving force and resistance of the vehicle in the process of driving. The driving force mainly includes the engine and hydraulic hybrid power system. The resistance mainly includes the rolling resistance, air resistance, and grade resistance. In order to be closer to the actual conditions and make the simulation model more accurate, the vehicle resistance calibration test is carried out on matching vehicles.

The test result is shown in Fig. 3, and the relationship between the vehicle resistance and the vehicle speed is obtained by quadratic fitting of the experimental data.

\[ F_t = 5.861v^2 + 8.814v + 2135.551 \]

4.2 Power coupling module

Taking the parallel hybrid as an example, the hydraulic hybrid system recovers the kinetic energy of the rear wheels. In driving condition, the secondary component and the engine drive the vehicle together by mechanical connection. In braking condition, the braking operation is completed by the friction braking power of the original vehicle and the re-regenerative braking power produced by the secondary component. The braking force distribution of the
The front and rear wheels is not changed without changing the operability and driving comfort of the vehicle. The front and rear brake distribution weight coefficients are as follows:

\[
\delta_h = \frac{F_{br_{max}}}{F_{fr_{max}} + F_{re_{max}}} = \frac{\delta_{fr} \cdot F_{h}}{\delta_{re} \cdot F_{h} + \delta_{fr} \cdot F_{b} - F_{hb/p}}
\]

\[
\delta_e = \frac{F_{re_{max}}}{F_{fr_{max}} + F_{re_{max}}} = \frac{\delta_{fr} \cdot F_{e} - F_{hb/p}}{\delta_{fr} \cdot F_{h} + \delta_{fr} \cdot F_{b} - F_{hb/p}}
\]

where \(F_{fr}\) is the front wheel maximum braking force (N); \(F_{re}\) is the rear wheel maximum braking force (N).

The power coupling module mainly includes the brake force distribution weight coefficient and the mechanical transmission. The braking force distribution coefficients of the front wheel and the rear wheel are, respectively, inputted into the sub-module of the weight coefficients. The mechanical drive part is constructed by the existing components of the machine library in the software.

### 4.3 Gearbox module

The gearbox is in the form of manual shift. The gear is shifted as the speed of the vehicle is increased during the driving process. In the braking process, according to the driving habits of the general driver, the gearbox keeps the current gear before braking. In this model, an eight-gear gearbox is used to simulate it. According to the actual gearbox, the gear speed and gear ratio corresponding to the vehicle speed are obtained as shown in Table 1.

In the AMESim simulation environment, a shift strategy of gearbox is established by means of signal library and function operation. At the same time, the corresponding transmission ratio is put into variable gearbox ratio reducer module to achieve the simulation of gearbox shift operation.

### 4.4 Hydraulic system module

The hydraulic system module mainly includes hydraulic secondary component, accumulator, and control valve group. In traditional simulation models, hydraulic pumps are generally regarded as ideal states while the volume efficiency and mechanical efficiency of the secondary component are neglected. In order to be closer to the actual vehicle and be more accurate, an efficiency module is added into the secondary component, which means the efficiency is substituted into the efficiency curve of each displacement pump in the matching process.

### 4.5 Engine module

The engine module outputs the corresponding torque according to the input control signal. At the same time, the engine module calculates the fuel consumption at this moment and makes hybrid vehicles work at higher efficiency according to the universal characteristic curve and the external characteristics of engine.

### 4.6 Vehicle control module

According to the actual demand of the vehicle, the system mainly adopts three operation modes: active energy charging mode, auxiliary braking mode, and hybrid mode. Active energy charging mode is used to charge energy to accumulator to assist engine drive vehicle climbing, before going upgrade for long distances. Auxiliary braking mode is used to auxiliary car brake, before going downgrade. The hybrid model is applied to the braking and starting conditions of the vehicle during its normal running, so as to realise the recovery and energy.

The control module mainly deals with the input cycle condition signal. The control signal is output to the clutch and secondary components, variable control, and other actuators after taking vehicle resistance, braking torque required by different gears, torque required, and braking torque by engine into consideration.

### 4.7 Hybrid vehicle AMESim simulation model

Each control module and function module are encapsulated into super components according to the above modelling and analysis. A complete simulation model of hybrid vehicles is obtained as the key part of global parameter matching and control strategy as shown in Fig. 4 below.

### 5 Operational results and experimental verification

Taking a heavy vehicle as an example, the global parameters are matched and optimised through the optimisation algorithm platform (Fig. 5). The vehicle body status parameters are shown in Table 1.

The main parameters are input into the simulation platform to set the parameter options (Table 2). By using the simulation platform, 10 sets of matching optimisation groups with higher fuel-saving rate are obtained, as shown in Table 3.

The optimal solution is selected with the results of tenth groups which is the highest fuel-saving rate. The vehicle experiment is carried out according to the tenth sets of matching results. The experimental results are evaluated by energy regeneration efficiency and fuel consumption. The experimental vehicle is tested from stationary acceleration to test braking speed, and then, the vehicle is braked to standstill with the hybrid system and friction braking system of original vehicle working together. At the same time, a part of kinetic energy is recovered and stored in accumulator. Then the vehicle is driven individually by hydraulic hybrid system to the maximum speed \(v_{ge}\) the vehicle has reached. The energy regeneration efficiency is defined as the ratio of the kinetic energy before and after the test:

\[
\eta_{reg, en} = \frac{E_{br} - E_{dr}}{E_{br} - E_{dr} - \Delta E_{fr}} - \frac{v_{br}^2}{v_{dr}^2}
\]

As shown in Fig. 6, the braking speed was set to 20 km/h in this energy recovery test. Fig. 7 is the experimental result of energy regeneration efficiency.

It can be seen from result of the experiment that the braking kinetic energy is recovered and stored in the accumulator by secondary component after the braking signal is sent out, and the accumulator pressure is about 24.7 MPa at this time. After the drive signal is issued, the accumulator pressure is about 22.3 MPa. The maximum speed of the vehicle is 6.2 km/h when it is driven separately by the hydraulic hybrid power system. The accumulator pressure decreased during the maintenance period because the oil leaked out which leads to the loss of energy. The energy regeneration efficiency of the experimental prototype is 13.1% after calculation.

The fuel gas recorder is installed on the experimental prototype to measure and record the fuel consumption of the vehicle. Through the experiment, as shown in Fig. 6, it can be seen that under the experimental conditions, the fuel consumption of the original vehicle is obviously higher than the fuel consumption of the hybrid vehicles. Through calculation, it can be concluded that the average fuel-saving rate of hybrid vehicles is 15.2% and the fuel consumption of the original vehicles is obviously reduced.

### Table 1 Relationship between the gear speed and gear ratio corresponding to the vehicle speed

| Vehicle speed, km | 5   | 10  | 15  | 20  | 25  | 30  | 35  | 40  | 45  | 50  | >50 |
|-------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| gear              | 1   | 2   | 3   | 4   | 5   | 6   | 6   | 7   | 7   | 7   | 8   |
| ratio             | 8.25| 6.04| 4.62| 3.23| 2.38| 1.72| 1.72| 1.24| 1.24| 1.24| 0.95|

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Basing on the multi-dimensional and non-linear characteristics of hybrid system, aiming at the fuel economy, this study adopts a simulation platform which was established on the combination of MATLAB, VBA EXCEL, and AMESim. Meanwhile, the parameters matching and control optimisation based on simulation model were proposed by this study. Through the analysis of the

**Fig. 4 Hybrid vehicle AMESim simulation model**
1-fixed pump control unit; 2-hydraulic unit; 3-vehicle driving unit; 4-engine unit; 5-vehicle control unit; 6-brakes unit; 7-gearbox unit

**Fig. 5 Hybrid optimisation platform**

**Table 2 Main parameters of the vehicle**

| Parameters                  | Values  |
|-----------------------------|---------|
| wheel radius, m             | 0.532   |
| vehicle mass, kg            | 22,000  |
| windward area, m²           | 6.73    |
| max speed, km/h             | 90      |
| final ratio                 | 4.87    |
| transmission ratio          | 8.25/6.04/4.62/3.23/2.38/1.72/1.24/0.95 |

**Table 3 matching optimisation groups**

| No. | $P_e$, kW | $V_{\text{max}}$ | $P_{\text{0, acc}}$ | $V_{\text{acc}}$ | $S_{\text{fuel}}$, % |
|-----|-----------|------------------|---------------------|-----------------|----------------------|
| 1   | 222       | 125              | 16                  | 63              | 16.60                |
| 2   | 270       | 90               | 18                  | 63              | 16.82                |
| 3   | 221       | 125              | 20                  | 80              | 21.08                |
| 4   | 232       | 90               | 16                  | 80              | 21.36                |
| 5   | 201       | 90               | 19                  | 80              | 23.25                |
| 6   | 221       | 180              | 15                  | 100             | 25.10                |
| 7   | 210       | 125              | 17                  | 100             | 26.36                |
| 8   | 221       | 90               | 16                  | 100             | 27.98                |
| 9   | 222       | 90               | 20                  | 126             | 32.24                |
| 10  | 232       | 125              | 16                  | 126             | 33.21                |

**6 Conclusion**

Basing on the multi-dimensional and non-linear characteristics of hybrid system, aiming at the fuel economy, this study adopts a...
vehicle structure, the study inputs every key parameter to the simulation module to determine and to achieve the global parameter matching and control optimisation. Among them, the simulation platform as a basis of judgment improves the accuracy and efficiency of the initial design for hybrid system development. The experimental results show that the optimised scheme meets the requirements of vehicle starting and energy recovery, and the rate of fuel saving reaches 15.2%.

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Fig. 6 Experimental result of energy regeneration efficiency

Fig. 7 Fuel consumption of the engine