Design and Application of Parallel Hybrid Vehicle Simulation Platform

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Abstract—**A parallel type hybrid-electric bus model is constructed to study hybrid powertrain and its sub-systems. The model is a forward-looking model based on LabVIEW simulation module. The engine, clutch and battery model were specially designed according to the target powertrain. Each part of the model is separately validated by test bench experiment. Part model behavior is compared with that of real target part on dynamic testbed and revised if it was inaccurate. First, offline simulation was adopted to validate rationality and accuracy of the part model. Then, the model was downloaded into a real-time target PC running LabVIEW real-time operation system to study the control strategy of hybrid control unit. Control strategy was studied under three different driving cycles: New York Bus Cycle, Manhattan Cycle, and China City Cycle. The simulation results show that the hybrid-electric bus with good control strategy can improve fuel economy and reduce exhaust emissions.**

Keywords-parallel hybrid; forward-looking; simulation; real-time;

I. INTRODUCTION

Diesel-electric parallel hybrid powertrain has the advantage of higher fuel economy performance and lower emission through hybridization with other energy storage devices such as battery or supercapacitor. Three methods are commonly adopted for R&D work of hybrid powertrain: computer simulation, test bench experiment and road experiment. As the accuracy of this three methods increasing, the cost also increases. Usually, computer simulation has the lowest cost and best flexibility, so we adopt it for powertrain Sub-parts parameter optimization and control strategy development in the very beginning of a powertrain design period. Then, test bench experiments were carried out for model validation and further optimization. Rapid prototype or target controller was applied for road experiment at last when the bus and its powertrain were ready.

As computer simulation has the advantage of low cost and fast developing speed, it is always choose to compare the different configuration of the powertrain and to estimate the fuel economy & emission improvement. Two representation of vehicle simulation software are PSAT and advisor. PSAT adopt the forward-looking simulation method and advisor chose the backward-looking simulation method.

The problem of simulation is that its accuracy and veracity need to be reassured. Powertrain parts such as internal combustion engine, clutch e.g. are no linear systems, ideal physical model of these parts are difficult to built. Empirical model is used for these parts based on experiment data. Some parts such as battery and motor are more likely to get physical model. But experiment parameters are also needed for the complexity to explain every factors that influence the model.

A dynamic test bench is used for part experiment and powertrain experiment to get the parameter of model and to validate the accuracy of the model. Steady map such as engine torque map and motor efficiency map were achieved on the test bed. Dynamic behavior were measured and described in the form of transfer function. The model is then validated in certain dynamic cycle to adjust its accuracy. Battery parameters are tested in a specially battery test bench according to HPPC test criterion.

Simulation model was constructed in LabVIEW graphic language rather than commonly used Simulink. It is because LabVIEW support better general controller as a real-time controller at low cost and its better support in human-machine interface. The model applied in offline simulation can be easily downloaded in real-time controller to carry out a HIL simulation by adding real hardware interface between HIL simulator and hybrid controller.

II. SIMULATION MODEL

A. Simulation System Description

A forward simulation model including engine, clutch, motor, transmission, battery, controller, driver and dynamic vehicle load is built in LabVIEW. The model is a forward-looking simulation model, in which torque and inertia is applied from engine to the vehicle wheel, and speed is the feedback from wheel to engine in the reverse direction. A driver model is also integrated in the simulation model to manipulate the vehicle to follow certain drive cycle.

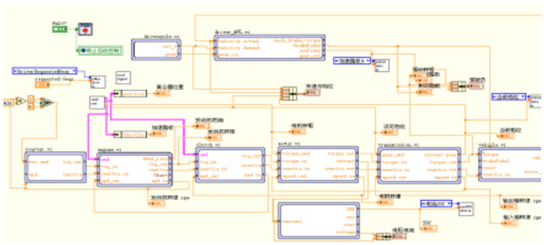

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Figure 1. Overall simulation model

B. Engine Model

The diesel engine model is based on Quasi-steady-state model. First, steady-state torque and efficiency map was measured and recorded in the lookup table. Engine torque and efficiency was calculated according to engine throttle and speed. Then considering the idle-speed control and engine inertia, output of the lookup table was adjusted by a delay block. If engine speed is lower than idle speed, engine torque is modified by a PID idle-speed control block. If engine control mode is set to speed control mode. Engine throttle is determined by a PI speed controller.

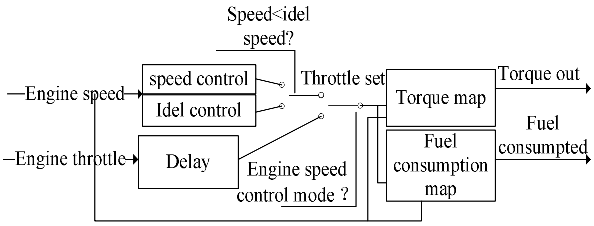

Figure 2. Engine model diagram

C. Clutch Model

The target clutch is an electric motor driven diaphragm spring clutch. Clutch includes three different operating states: separated, sliding and engaged. when clutch is in separated and engaged mode. the model is quite simple. but when it comes to the sliding mode, the torque passed from driving disk to driven disk is hard to determinate. the torque must be a continues force due to the experiment data. Simply judging the clutch mode according to the speed difference of the driving disk and driven disk will lead to a jump change of the output force. To solve this problem, dynamic friction coefficient is defined to calculate the dynamic friction torque.

$$\mu_{ds} = a - bu - a \cdot e^{-cu} \tag{1}$$

where a, b and c are determined by the material, u is the speed difference between the driving disk and driven disk.

Then, the torque is calculated by the formula below.

$$T_C = \begin{cases} 0 & T_{CS} = 0 \\ sign(\omega_e - \omega_c) \cdot \mu_{ds} \cdot F_N \cdot R_C + \lambda \cdot T_e & \Delta\omega \neq 0 \\ T_e & T_{CS} > T_e \end{cases} \tag{2}$$

T_e is the engine torque, T_{CS} is the clutch split friction torque, F_N is the clutch normal pressure force. Rc is clutch disk radius. λ is input torque influence coefficient. μ_{ds} and λ is shown as Fig.3. When the speed difference is small, clutch output torque is mainly determined by input torque. When The speed difference is large, torque passed by clutch disk is determined by clutch normal pressure and the dynamic friction coefficient.

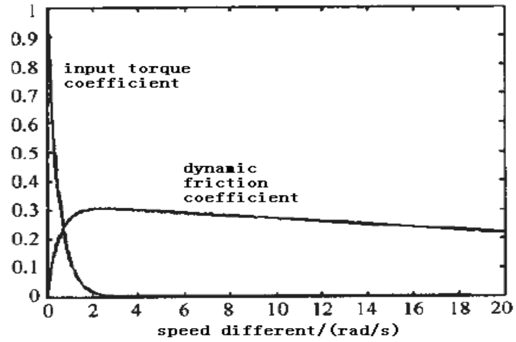

Figure 3. Clutch dynamic coefficient

D. Electric motor

Motor static and dynamic parameters are measured in the testbed and used in the look-up table of the motor model. Motor torque is limited by the external characteristics of motor. Motor current is calculated according to the efficiency map as demonstrated in Fig.4.

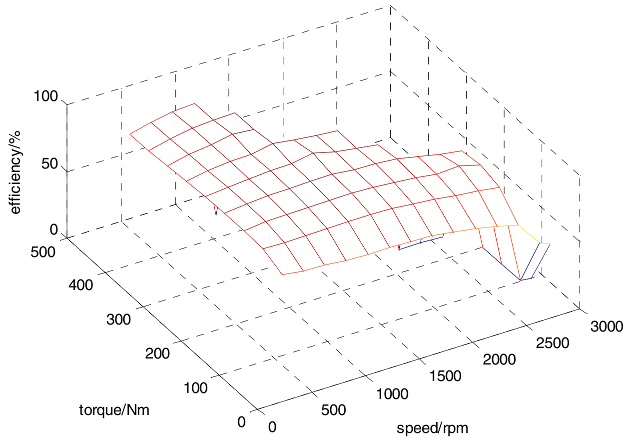

Figure 4. Motor efficiency map

E. Battery

This paper adopt one equivalent circuit model-PNGV model that can describe the battery charge and discharge dynamic characteristics. As shown in Fig. 2, V_{oc} denotes battery open circuit voltage. R_0 denotes the battery ohmic internal resistance. R_p denotes the battery polarization resistance. C_p denotes the battery polarization capacitance, I_L denotes the battery load current. I_p denotes the polarization resistance current. V_L denotes the battery voltage.

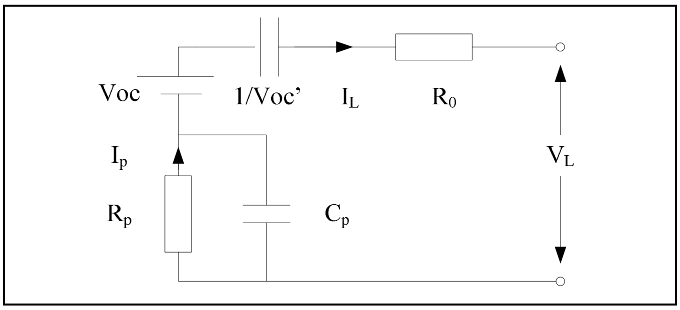

Figure 5. PNGV battery model

Battery parameters are estimated by HPPC(Hybrid Pulse Power Characteristics) test according to FreedomCAR Battery Test Manual For Power-Assist Hybrid Electric Vehicles. Battery current and voltage is shown in Fig. 6.

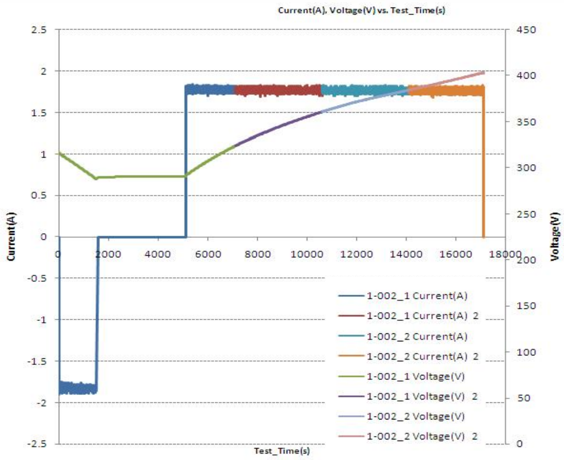

Figure 6. Battery voltage and current test

III. Test Bench Experiment and Model Validation

Fig. 7 shows configuration of the hybrid powertrain experiment research platform. It consists of diesel-electric hybrid powertrain, dynamic dynamometer and its controller, test system, and real time control system.

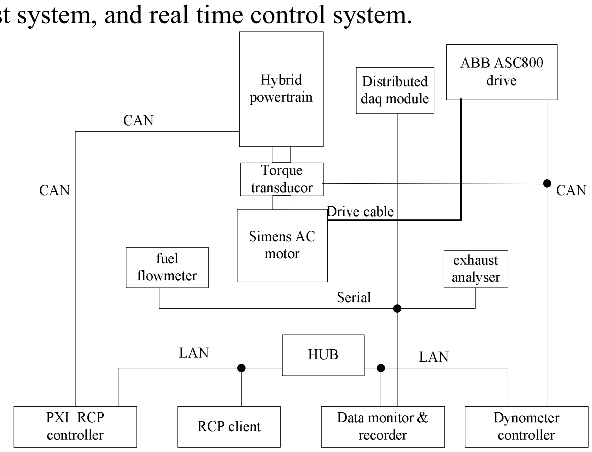

Figure 7. Configuration of Experiment Research Platform

Based on dynamic testbed, sub-systems of hybrid powertrain are tested and model behaviors are validated by test results.

Three different driving cycles are employed: New York Bus Cycle, Manhattan Cycle, and China City Cycle. Sub-systems worked under supervision of the HCU(Hybrid Control Unit). Real-time data were recorded and compared with simulation data to check the difference between model and practical components.

A. Engine Model Validation

Engine Model was validated by dynamic experiment. Engine was given a throttle command. Engine speed is observed. Simulation result shows good coherence between the experiment engine speed and simulated engine speed.

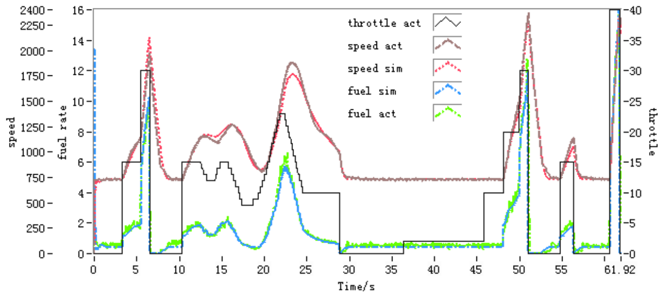

Figure 8. Engine model validation

B. Battery Model Validation

Battery Model was given the same current input as experiment in dynamic charge and discharge cycle. Simulated battery voltage and SOC were compared with that measured in experiment cycle. Results shows good coherence between the model and the practical part. The max error is 4.26%.

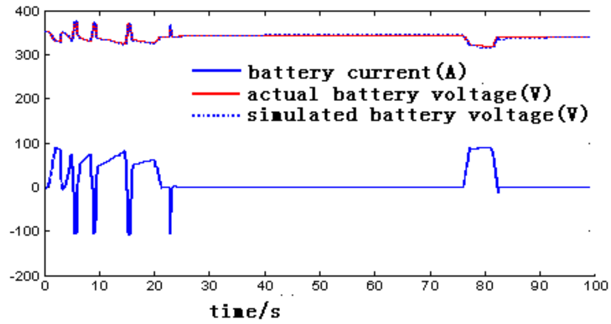

Figure 9. Validation of the battery PNGV model

C. Clutch Model Validation

To validate the clutch model, an experiment was firstly carried out in test bench. The dynamometer performed as the road load simulator. A controller sent position command to the clutch controller to make a smooth combination of the clutch. Clutch model was then simulated by given some experiment data input to validate its torque output and driving disk input. As demonstrated in Fig.10, engine throttle command, clutch command and clutch driven disk speed is given the same value as it's movements in the testbed experiment. Clutch output torque and the driving disk speed is observed and compared with the experiment data. As in Fig.11, the simulation result shows good coherence with the experiment data.

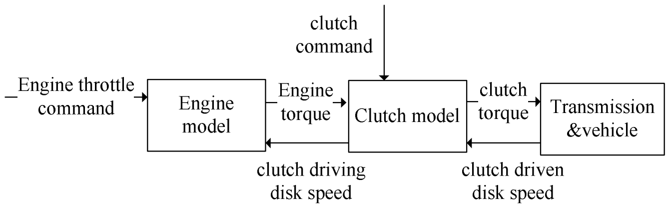

Figure 10. Clutch model validation diagram

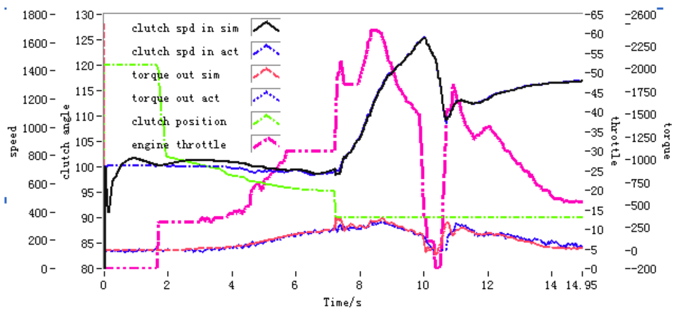

Figure 11. Clutch model validation

IV. OFF LINE SIMULATION WITH CONTROL STRATAGY

After validating the part models. The part model was then integrated into a powertrain model.

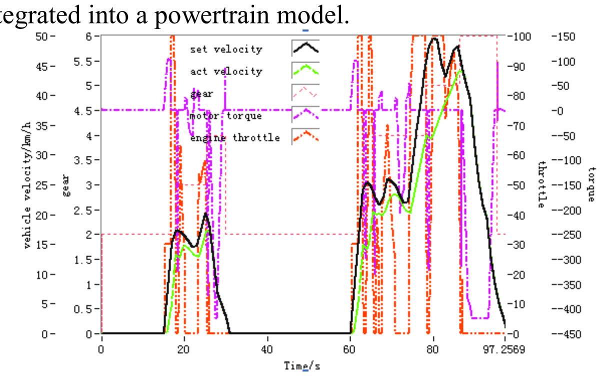

Figure 12. Powertrain control simulation

Control strategy was studied under three different driving cycles: New York Bus Cycle, Manhattan Cycle, and China City Cycle. The simulation results show that the hybrid-electric bus with good control strategy can improve fuel economy and reduce exhaust emissions. Simulation result shown in Table I demonstrated the improvement in fuel economy. Hybrid system can achieve about 17% economy improvement compared to the traditional internal combustion engine drive powertrain in the three cycle tested.

TABLE I. CYCLE SIMULATION RESULT

Cycle	***Fuel economy in hybrid mode (L/100km)***	***Fuel economy in traditional mode (L/100km)***	***improvment***
China City Cycle	25.43	30.56	16.78%
Manhattan Cycle	38.06	45.80	16.8%
Newyork Bus Cycle	46.81	57.2428	17.8%

Simulated velocity and gear command in China city cyle is shown as Fig.13. Simulated motor torque and engine throttle command is shown as Fig.14.

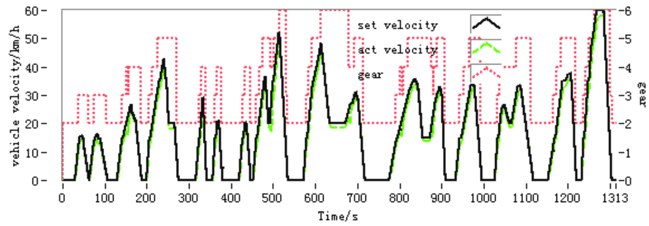

Figure 13. Simulated velocity and gear command in China city cycle

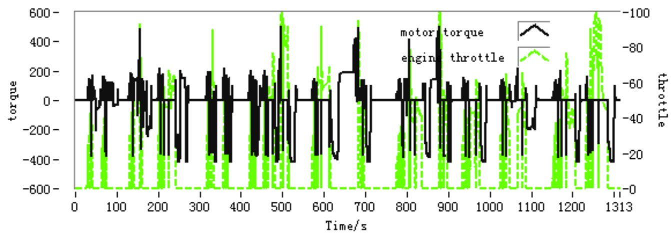

Figure 14. Simulated motor torque & engine throttle command

V. REAL-TIME SIMULATION

After validation of the part model, the simulation system was downloaded into a target computer through LAN connection to execute real-time simulation. The target computer running LabVIEW real-time operation system get command from HCU though CAN and Digital IO interface while sending its simulation states to HCU in the same way. This test method can not only verify the control strategy but also simulate part fault to check the robustness of the control algorithm.

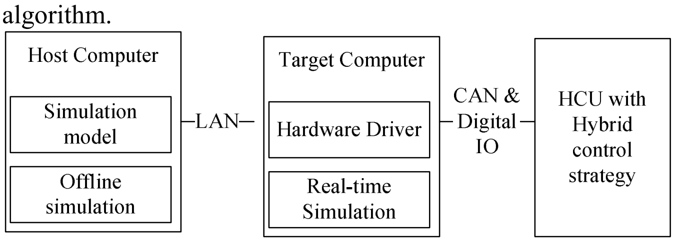

Figure 15. Hardware-in-the-Loop Test

VI. CONCLUSION

In this study, a simulation research platform for diesel-electric hybrid powertrain is developed based on LabVIEW simulation module. Sub-systems of diesel-electric hybrid powertrain are tested and characteristic parameters are obtained from test data. HIL controller is realized on a PXI platform at a low cost. Application of this platform shows it is a powerful tool for hybrid powertrain research and development.

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