Research on Simulation System Model of Diesel Engine Applied to Virtual Calibration Development

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Abstract. In order to meet the increasingly strict emission regulations, more complex control systems are used in the engine, which increases the calibration workload by several times. Virtual test bed is a method to greatly reduce the calibration cycle, workload and cost by replacing the real engine and vehicle for the hardware in the loop virtual calibration research. Virtual calibration process mainly includes experiment design, virtual experiment, model construction, data optimization, MAP generation and calibration result test. This paper mainly describes the establishment method of the simulation model of diesel engine of China 6 applied to virtual calibration based on the AVL CRUISE™ M and MoBEO™. The differences between the test results and the simulation results under the steady-state and transient conditions of the model were compared. The results of stationary mode and cold WHTC show that the model is of good quality and can be used in the research of virtual calibration development.

Keywords: Diesel engine, virtual calibration, simulation, CRUISE M.

1. Introduction
In order to meet the increasingly strict limit requirements of emission laws and regulations, OEMs all over the world have begun to adopt new technologies and new design schemes, which makes the control system of engines and post-processing increasingly complicated [1]. In addition, under the influence of environmental conditions such as altitude and temperature, the power and economy of diesel engines are reduced, and the emission is deteriorated, which leads to problems such as the increase of diesel engine thermal load, the overspeed of turbocharger and the over-limit of pressure in cylinder, resulting in a doubling of the engine calibration workload [2].

Virtual Test Bed (VTB) is a vehicle virtual simulation bed based on hardware-in-the-loop test system which can replace real engine and vehicle [3]. It mainly includes software simulation model, hardware-in-the-loop test system and high-quality test data. Except ECU is real, other modules of VTB are simulated by simulation model [4]. The virtual calibration process mainly includes experiment design, virtual experiment, model construction, data optimization, MAP generation and
calibration result test. Virtual calibration by VTB can greatly reduce the calibration cycle and workload, and thus reduce the cost of calibration [5-6].

With the rapid development of electronic control technology, virtual calibration has become the main research direction in this field [7]. Based on CRUISETM M software of AVL, a domestic diesel engine simulation model was established in this paper. The differences between test results and simulation results under steady and transient operating conditions were compared respectively. Both normal mode and cold WHTC show good model quality, which indicates that this model can be used in the development and research of virtual calibration.

2. Cruise-M modeling process

Cruise-M name in the “M” is for the English word “multi-disciplinary”, meaning “multidisciplinary, multiple physical fields”. The software designed specifically for the vehicle more physical system simulation, combined with highly flexible and multi-level modelling method, and integrated the third-party tools of FMI of standard interface, can the seamless thermodynamic cycle, the engine exhaust gas purification plant system, cooling and lubricating system, vehicle transmission system and control system integrated into a unified simulation platform [8].

In this paper, Cruise-M software is used to build a simulation model of a China 6 diesel engine which diesel engine intake is supercharged and intercooled, cylinder form is 4 cylinders in line with 4 valves, rated power is 147kW and rated speed is 2300rpm. The main technical parameters of the engine are shown in Table I.

| Tab. 1 Main specifications of diesel engine |
|------------------------------------------|
| **Item**                              | **Specification**            |
| Fuel Type                             | Diesel                      |
| Cylinder Arrangement                  | Inline                      |
| Number of Cylinders [-]               | 4                           |
| Bore Diameter × Stroke [mm × mm]     | 105×120                     |
| Displacement [L]                      | 4.156                       |
| Number of Valves per Cylinder [-]     | 4                           |
| Cylinder Center Distance [mm]        | 120                         |
| Intake Type                           | Turbocharged and intercooled|
| Emission Standard                    | CN VI                       |
| Rated Power [kW]                     | 147                         |
| Rated Speed [r/min]                  | 2300                        |
| Net Power [kW]                       | 142                         |
| Maximum Horsepower [hp]              | 200                         |
| Maximum Torque [N.m]                 | 720                         |
| Maximum Torque Speed [r/min]         | 1200~1600                   |
| Idle Speed [r/min]                   | 675±25                      |
| Maximum No-load Speed [r/min]        | 2530±30                     |
| Emission Technology Route            | HPCR+EGR+DOC+DPF+SCR        |

The establishment of the simulation model applied to the development of virtual calibration is divided into three steps. In the first step, only the main geometrical data of the engine are used as input for model set-up on concept model phase. The gas path is established and the properties of each module are set. At the same time, mechanical connection, electrical connection and signal connection are carried out for each scattered module respectively according to the transmission route of power, fluid and heat and the control logic of signals. Connect the interface block and signal routing and sub-model to the gas path. Measurement data is used to make a refinement of the model to increase
accuracy on intermediate model phase. Third, the model is adapted to measured steady state and transient data. Highest accuracy which is needed for model-based calibration.

3. Sub-model construction and parameter setting

3.1. Gas path

The construction of gas path involves a lot of theoretical knowledge, including pipeline heat transfer, aerodynamics, pressure fluctuation, etc., so the expression of the corresponding mathematical model is very cumbersome. Firstly, the relevant modules and basic components of the air system in the model construction process are selected according to the engine layout, and the correlation is completed according to the actual requirements. Then, the indexes of the selected components are adjusted and improved according to the relevant technical parameters such as the operating conditions of the diesel engine.

The gas path of the engine model in this paper connected engine with ambient in, air filter, compressor, charge air cooler, throttle valve, intake manifold, turbine, EGR circuit, EAS, muffler and ambient out according to the engine layout as shown in figure 1. Figure 2 shows the gas path model of this engine.

The most important thing to calibrate gas path is to calibrate pressure and temperature. Therefore, during the establishment of gas path, it is necessary to set the parameters of each component successively, compare the pressure and temperature simulation results of each sensor position with the test results, and then adjust the parameters of the components.

![Fig. 1 Engine layout.](image1)

![Fig. 2 Gas path](image2)
3.2. Restrictions
The air filter, charge air cooler, throttle valve, turbine bypass, and muffler of this model were all represented by restriction components. Restriction is a resistance unit, used to simulate the flow resistance when the gas flows through the pipeline, structural parts. Heat transfer loss through the components were not considered, so there is no need to add solid wall, etc., into the model. The reference diameter or reference area and traffic coefficient of restriction were set according to the attributes of each component.

The Restriction element solves the orifice equation as follow. In the formula, \( \mu \) represents flow coefficient, \( \beta \) is a flow function (different formulation for subsonic and sonic flow conditions) that depends on the specific heat ratio of the gas and on the pressure ratio \( \frac{p_{out}}{p_{in}} \) across the restriction. \( R_{in} \) is the upstream specific gas constant.

\[
m = \mu \cdot A_{ref} \cdot p_{in} \cdot \beta \cdot \left( \frac{2}{R_{in} + p_{in}} \right)^{0.5}
\]

3.3. Plenums
A plenum is often used as a connecting element of two transient components. Since the gas path in CRUISETM M is calculated as a zero-dimensional system, plenums are typically used to account for the volumes of specific pipe sections of the engine. The sensors in this model are represented by the plenum’s element.

Starting from each plenum, a thermal path was built to model the heat transfer towards the environment: the structure of the path consists in a convective heat exchange between the gas within the volume and the solid wall, and in another convective heat transfer between the solid wall and environment.

3.4. Turbocharger
Turbocharger model is composed by three resistive components: compressor, turbine and wastegate. CRUISETM M can interpolate the data of the turbocharger provided by the supplier under some working conditions, so as to obtain the turbocharger map in a wider range.

3.5. Engine
In this paper, MoBEOTM is used to build a diesel model. MoBEOTM is short for Model Based Engine Optimization. MoBEOTM can quickly and intuitively model based on limited input data. Moreover, it has certain extrapolation capability, and the established model can meet the precision required by conceptual design [8]. The test data entered in the MoBEOTM model is used to automate the calibration of the engine through Wizard. Some calibration results are shown in figure 4. It can be seen that the accuracy achieved by Wizard automatic calibration is acceptable. During the automatic calibration of engine, if the manual setting option of corresponding data is turned on, this part of data will not be changed during the wizard process.
4. Results

4.1. Engine stationary results
Stationary conditions include 198 points as shown in figure 5. The deviations between measurement and simulation are shown in table II. The results showed that the deviations of max cylinder pressure, IMEP, BMEP and soot from engine outlet were under 5%, and deviations of other characteristic parameter were acceptable.
Tab. 2 Deviations between measurement and simulation results

| Characteristic Parameter       | Deviation [%] |
|-------------------------------|---------------|
| 50% Mass fuel burnt           | 13            |
| Max cylinder pressure         | 3             |
| IMEP                          | 0             |
| BMEP                          | 0             |
| BSFC                          | 6             |
| NOx emissions engine-out      | 14            |
| SOOT emissions engine-out     | 1             |

4.2. Engine transient results

Transient condition is World Harmonized Transient Cycle, and the change of speed and torque with time is shown in Fig. 8. Figure 8, 9 and 10 show the Intake air mass flow, NOx emissions engine out and Soot emissions engine out over time. The results show that the error of the transient index is less than 10%, which indicates that this model can be used in the research of virtual calibration development.

5. Conclusion

In this paper, a simulation model established method based on the CRUISE™ M and MoBEO™ of a diesel engine of China 6 applied to virtual calibration is presented. The results of stationary mode and transient mode of cold WHTC shows that the model is of good quality and can be used in the research of virtual calibration development.
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