Engine Transient Characteristics Simulation Technology using Zero-dimensional Combustion Model

The transient characteristics of an engine are one of the important evaluation indexes related to the operability of a vehicle. We have developed a diesel engine zero-dimensional combustion model that can calculate the engine combustion cycle in a short amount of time on the order of several seconds based on combustion simulation models that we have established. This paper presents a simulation technology that utilizes this zero-dimensional combustion analysis to accurately estimate the transient characteristics of an engine. The use of this simulation model allows an engine system to be optimized before the production of a prototype through the evaluation of various vehicle operating patterns, and therefore contributes to shorter vehicle development times.

1. Introduction

Diesel engines have been utilized as power sources for various vehicles including industrial machines, construction machines, agricultural machines, etc., due to their high thermal efficiency and high usability. On the other hand, emission controls are becoming increasingly stringent every year, mainly in advanced countries. To comply with these emission controls, electronically controlled fuel injection systems, exhaust gas recirculation (EGR) systems and after-treatment devices such as diesel particulate filters (DPF), have been developed and applied to latest multi-purpose diesel engines. However, the adoption of these technologies made engine systems complicated and results in the problem of increased development man-hours caused by an increase in design parameters. Particularly in the case of multi-purpose diesel engines for which turbocharger specifications and control parameter setting values need to be changed depending on the vehicle because a certain type of engine is used for various vehicle purposes, the reduction of the man-hours required for this optimization is directly linked shorter vehicle development times.

The rotation speed and load of an engine change in various patterns depending on the vehicle application. The transient characteristics for each of the patterns are one of the important evaluation indexes related to the operability of a vehicle. Generally, the transient characteristics are evaluated using the prototype engine mounted on a vehicle. In this evaluation, acceleration capability in response to the pressing of the acceleration pedal, engine speed setting in response to a sudden increase of applied torque, etc., are checked. The transient characteristic simulation model presented in this paper is used for the evaluation of the transient characteristics in the initial phase of engine development and the optimization of the engine system. By incorporating a zero-dimensional combustion simulator that can estimate the combustion condition in an engine...
combustion chamber in a short amount of time on the order of several seconds and a control model equivalent to an actual engine into an engine performance calculation model, various operating patterns can be evaluated on the calculation model in a manner similar to an evaluation using an actual engine. The utilization of these analysis technologies for the evaluation of the transient characteristics for various operating patterns in the initial phase of engine development before the production of a prototype allows minimal post-process vehicle evaluation and the enhancement of development efficiency.

2. Diesel engine zero-dimensional combustion model

During a transient state of an engine where its rotation speed and load change suddenly, state quantities in the intake and exhaust systems positioned upstream and downstream of the combustion chamber change from moment to moment. This change of state quantities affects the combustion state in the combustion chamber and eventually the responsiveness of the engine. Therefore, the accurate evaluation of a transient state requires a combustion simulator for the evaluation of the effects of change in state quantities in the intake and exhaust systems on combustion. It also requires the calculation of a number of combustion cycles. Because as many as several tens to several hundreds of calculations are needed even for a several-second operating pattern, a zero-dimensional combustion simulator that can implement calculations in a short amount of time on the order of several seconds is necessary. The calculation method and the calculation accuracy of this zero-dimensional combustion simulator are described below.

2.1 Calculation method

We established a phenomenology-based diesel engine zero-dimensional combustion simulator on the basis of previously-published empirical formulas and sub-models related to combustion in a diesel engine and efforts on three-dimensional combustion analysis technologies. The zero-dimensional combustion simulator adopts a multi-zone model as its basic concept and is a zero-dimensional simulator that does not have the concept of space, yet it can perform calculation in consideration of the non-uniformity state of injected fuel spray. Figure 1 shows a schematic view of the multi-zone model adopted by the zero-dimensional combustion simulator. Fuel injected from the injector is handled as spray packages separated for each time step, and air entrainment, fuel evaporation, ignition, combustion, exhaust gas production, etc., are calculated for each package.

2.2 Calculation results

We acquired test data using a diesel engine while changing the fuel injection timing and the injection pressure in order to verify the accuracy of the zero-dimensional simulator. As shown in Figure 2, the calculation results of the pressure inside the combustion chamber and the heat release rate reproduced the actual measurement at a satisfactory level of accuracy for every change.
3. Transient characteristic simulation

3.1 Calculation model

Figure 3 shows a schematic view of the calculation model used for transient characteristic simulation. For the creation of an engine performance calculation model, GT-POWER, commercially available performance calculation software developed by Gamma Technologies of the U.S. is used, and the zero-dimensional combustion simulator described in the previous chapter is integrated to obtain heat release patterns in the combustion chamber. Because a control model for controlling the fuel injection amount, the fuel injection pattern, the EGR, etc., is incorporated into this calculation model as is in an actual ECU (Engine Control Unit), control parameters can be input as in the case of an ECU. Therefore, it is possible to carry out the optimization of the engine system and control parameters while evaluating the transient characteristics on the analysis model.

3.2 Evaluation of transient characteristics

Figure 4 shows the operating pattern evaluated this time and changes in the cylinder internal heat release rate. With the engine controlled so that its rotation speed was maintained at a certain level, load torque applied to the engine was changed in a stepping manner and the stabilization of the engine rotation speed was evaluated. The evaluation object was a four-cylinder diesel engine.
with a turbocharger with the characteristics shown in Table 1. The rotation speed dropped immediately after a change in a stepping manner because the engine torque could not keep up with the change of the load torque. This reduction in the engine rotation speed causes the lowering of the operability of the vehicles on which the engine is installed. Therefore, one of the capabilities required for engines is to have higher transient responsiveness in order to raise the engine torque quickly and suppress the reduction in the engine rotation speed.

Table 1  Engine specifications

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<tr>
<td>Bore × Stroke</td>
<td>mm</td>
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<tr>
<td>Number of cylinders</td>
<td>4</td>
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<tr>
<td>Displacement</td>
<td>Lit</td>
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<td>Fuel injection system</td>
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<td>Intake system</td>
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<td>Exhaust gas recirculation</td>
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Figure 4  Evaluated operating pattern and change in cylinder internal heat release rate

Figure 5  Comparison of simulation results and experimental results of transient characteristics

The calculation results of the rotation speed lowering behavior caused by an increase of the applied load torque matched well with the actual experimental results, and therefore a satisfactory level of accuracy was attained. In this calculation, a combustion analysis using the zero-dimensional simulator was performed for all combustion cycles, and the heat release pattern that changes moment by moment during a transient change as shown in the lower section of Figure 4 was calculated. This allowed a change in combustion during a transient state to be reflected in the calculation results and resulted in higher calculation accuracy.
Figure 6 presents an example of a study for improvement in transient responsiveness through the optimization of turbocharger specifications and control parameters. After the optimization, the lowering of the engine rotation speed caused by a change in a stepping manner was improved significantly in comparison to before the optimization. In this way, the use of this simulator allows the optimization of a turbocharger and control parameters through theoretical study before the production of a prototype engine. This makes it possible to complete evaluation testing after the production of the prototype in less time, and therefore leads to shorter vehicle development times.

![Figure 6 Results of study for improvement in transient responsiveness](image)

4. Conclusion

The transient characteristics of an engine are one of the important evaluation indexes related to the operability of a vehicle. We created a diesel engine zero-dimensional combustion simulator that can calculate the engine combustion cycle on the order of several seconds based on combustion simulation technologies that we had established. By incorporating this into the multipurpose engine performance calculation code, we have developed a simulation technology that accurately estimates the engine transient characteristics. The utilization of this simulation technology for carrying out the development of an engine allows the optimization of complicated engine systems such as a turbocharger, after-treatment devices, and an EGR system before the production of a prototype through the evaluation of various vehicle operating patterns. In the future, we will utilize this simulation technology to carry out engine development quickly in tandem with vehicle development.

References

1. Hiraoka, K. et al., Development of Combustion Simulation for Off-Road Engine (First Report), 2015 JSAE Congress (Autumn)