

Real-Time Crank-Resolved Engine Simulation for Testing New Engine Management Systems

GianCarlo Pacitti, Steven Amphlett, Peter Miller, Robert Norris and Anthony Truscott
Ricardo UK Ltd

Copyright © 2008 SAE International

ABSTRACT

The development of control strategies for new Engine Management Systems requires a simulation tool to represent a model of the engine such that these strategies can be tested and verified. Current simulation tools for hardware-in-the loop (HiL) testing are limited to mean-value engine models. Although these lumped parameter type models are sufficient for current production Engine Management Systems, new technologies are emerging that would require sophisticated modeling tools to support the development of more complex systems such as closed-loop combustion control and for more thorough testing of onboard diagnostics. However, such hi-fidelity models have traditionally been distributed parameter typed models (e.g. WAVE), reserved for engine design purposes and therefore inappropriate for real-time testing.

A new piece of software has been developed to bridge the gap between distributed and lumped parameter models. This is physically based, with crank resolved in-cylinder models and accurate capture of wave propagation effects in the air path. As such it provides a more accurate transient response than mean-value models. The software is designed to run in real time, enabling it to be used in HiL systems to prove out the control systems surrounding the engine model. Furthermore, the model can be directly and automatically converted from donor WAVE models allowing the engine to be accurately modelled before being converted to the real-time implementation thereby greatly reducing development timescales.

The new tool chain has been validated with respect to a 4-cylinder turbocharged diesel engine with variable geometry turbine, EGR circuit and intercooler. Work is underway to show that this process provides an improvement to control strategy development time on a project.

INTRODUCTION

Reducing fuel consumption and emissions of internal combustion engines is a goal that will only be achievable with advanced new control system design. These control strategies in turn can only be developed by harnessing a simulated model of the engine, enabling testing and verification. Bringing a new ECU into production requires a tool-chain that can link the design, development and testing stages to provide fast, reliable results in short timescales. The most efficient process available will ultimately provide cost savings to the manufacturer.

The difficulties with testing a new control strategy for an ECU are numerous. The control systems engineer requires a calibrated engine model on which to test and validate the strategy. This often involves awaiting the results of engine running on a testbed. Confirming the results on a HiL rig necessitates a fast-running model, with simulation accuracy generally suffering as a consequence. This testing process is important for ensuring the ECU performs as desired, and performing a certain amount of virtual calibration on a HiL rig can save valuable time calibrating on a vehicle down the line, as well as improving engine performance under certain conditions [1], [2].

Testing new ECUs will become more important as the complexity of the units and the control strategies they store increases. The future of ECU production and control system design can be split into two parts; the methodology of the control system, and the complexity of the systems being controlled.

As the processing power of ECUs increases, the size and complexity of the information stored in them will also increase. It is conceivable that there will be a shift away from map-based calibration of control parameters to model-based control. Storing a calibrated model of the engine in the ECU and running it in parallel with observers of the actual engine will enable advanced control methods to be used, as well as enabling the rate of wear of the engine to be monitored as model

parameters are seen to be drifting. This will not only provide increased performance as the engine calibration adjusts to optimise engine efficiency with ageing, but added functionality to be able to provide on-board diagnostics to the driver or mechanic as to the state of the engine. An estimate of engine air-flow and in-cylinder physical parameters from the model will be very beneficial for control strategies.

More complex control strategies will be implemented in future ECUs, such as closed-loop combustion control. As more control variables are available (valve lift and timing, VGT position, multiple fuel injection quantities and timing, EGR valve position, variable intake manifold, dual fuel engines, 2/4 stroke switching), control strategies will become inherently more complicated, and validating the interactions between them will insist on an accurate and physically transparent engine model.

This paper presents a new piece of software for developing real-time in-cycle engine models directly from engine design software. The solution developed provides a link in the tool-chain to allow development and testing of control strategies to begin at an earlier stage, with more accurate results and in a shorter timescale. The model is then validated against the high-fidelity simulation of the original engine design simulation.

REAL-TIME CRANK-RESOLVED ENGINE SIMULATION

In this section the current state of engine modeling for control system testing is described, followed by a description of the real-time in-cycle model and how it fills a gap in the existing systems.

THE STATE OF CURRENT ENGINE MODELLING

A distinction can be made between the classes of models that are used in engine simulation. These are lumped parameter models (fast but less accurate) and distributed parameter models (slow but very accurate).

Mean-Value Engine Models

Current systems used for testing engine control strategies on a HiL system are generally reliant on Mean-Value Engine Models (MVEMs) for a plant model. These lumped-parameter models are fast enough to run in real-time on a HiL system, and their performance is good enough for current control system testing. In this type of engine model the cyclic varying flow in the engine air-path is approximated by continuous flow. They have their limitations in performance, and also in their generation from a process point of view. The performance limitations of MVEMs can be summarized as

1. All cylinders treated as identical
2. No wave or tuning effects
3. Empirical corrections
4. Poor capture of transient effects
5. Combustion model based on look-up table

The first limitation described is a major hindrance to the development of control systems that depend on separate control of cylinders, for example independent fuel injection timing for closed-loop combustion control. This requires that the state of each cylinder is known individually in order to tailor the control effect for the cylinders both in isolation and collectively.

Without modeling any wave effects the contribution of this phenomenon to engine breathing performance cannot be included in the transient behaviour of the simulation [3]. Manifold tuning can be accounted for in maps for volumetric efficiency, but these maps are generally derived for steady state performance and will not be correct during transient events. This is particularly relevant to variable intake manifolds, variable valve trains etc. Furthermore, with the growing complexity of air systems such as multi-turbocharger systems, a lot of effort is required to correct for wave effects in order to have a representative model.

Using look-up tables instead of a combustion model leads to problems of dimensionality. As more control parameters are desired, the size of the map will increase, increasing the time taken to run the model, and also the time taken to produce the map for the model, as much more data is required. In order to reduce this dimensionality problem, the control calibration is often embedded within the map. An example of this is mapping thermal efficiency, as a 2-D function of engine speed and fuel quantity. This would inherently have the timing calibration embedded within the map. To get around this limitation, empirical corrections are often applied to the map to cater for up to six injections. This would inevitably lead to serious limitations on the model.

Generating these types of models provides further limitations to this approach. Once configured, MVEMs are generally parameterized from engine test-bed data, or from a 1-D engine simulation of the design (Fig 1). In the first case this can lead to a significant delay between the engine design and the construction of a model for HiL testing, pushing back the start of control strategy validation.

Artificial Neural Networks

Artificial neural networks (ANNs) provide a fast method of modeling complex processes with good prediction results [4]. They have shown to be a useful replacement for engine maps by mimicking the behaviour of complicated functions. Examples include using them to find:

- Cylinder pressure as a function of injected fuel mass and start of injection timing
- Volumetric efficiency as a function of engine speed, fuel mass, inlet and exhaust temperature and pressures.
- Energy transfer corrections for pulsating flow through turbochargers.

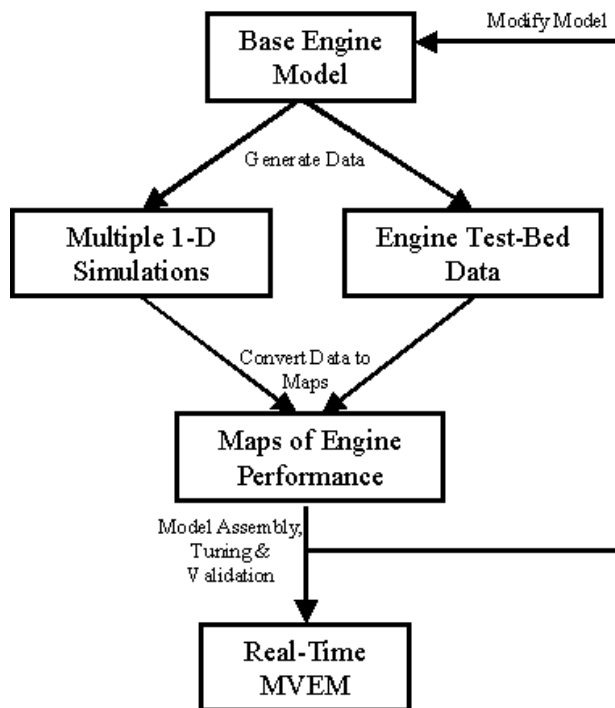


Fig 1 – Process to parameterize a MVEM

By imitating the performance of part of the engine with an ANN, the underlying physical processes of the engine are masked. This lack of visibility of the physics is a drawback if we wish to understand better how the control strategies implemented affect the internal workings of the engine. If a control strategy appears not to be working during validation, it may be difficult to discover from where exactly the issue arises.

ANNs are therefore not normally applied to model an entire engine. They are often utilized in conjunction with a physical model such as a MVEM.

Aside from the limitations associated with MVEMs, there are process issues arising from the use of ANNs. Firstly there is the combination of requiring a large amount of data to train the networks on, and the amount of time this takes. Without enough training data the ANN is not useful, as it will not return appropriate results from new data. Consequently, there also needs to be extra test data on which the ANN can be validated. As the number of desired control variables increases, the size of the training and test data will increase dramatically. The source of this data will either be the results of slow, high-fidelity simulations, or test-bed results.

Phenomenological Combustion Models

These crank-resolved models are good estimators of the combustion processes inside the cylinder. The physical basis of these models means that they do not rely on maps during their simulation. However, the model components outside of the combustion chamber up till now have been mean-value, with their inherent

limitations, particularly the lack of wave-effect modeling, which can have a large effect on the flows into the cylinders. They also rely on engine mapping data in order to calibrate the model. Their speed and performance does however make them suitable for HiL applications.

1-D Simulations

Simulation tools such as WAVE, GT-POWER and AVL BOOST have a long history and are well established. These distributed parameter models, based on the numerical solution of 1-D Navier Stokes flow equations, are primarily geared towards engine design. By solving the partial differential equations governing the flow, a full description of the complex phenomena in the manifold (acoustics, heat transfer, friction, junctions, moving valves and throttles) and processes in the cylinder are obtained. The inclusion of additional models for additional processes, such as structural heat conduction, create a modeling tool with predictive accuracy. The solver used is typically a variable-step solver. This coupled with the speed (>40 times real time) of such a comprehensive simulation makes these models unsuitable for HiL testing. Nevertheless, they are useful in producing results for validating MVEMs, and their ability to capture transient effects well has been effectively used in the past for control strategy development.

3-D Simulations

The most predictive simulations involve solving the full unsteady 3-D Navier Stokes equations. These simulations, such as the KIVA or VECTIS codes, typically discretize the flow domain into thousands or even millions of volumes. Due to the computational power required, they are normally restricted to individual components where detailed flow information is required, or for in-cylinder simulations where fuel spray, combustion and emissions formation can be predicted.

REAL-TIME IN-CYCLE CRANK-RESOLVED MODEL

From the previous section we can see that there is a trade-off between simulation time and modeling accuracy. There remains a demand in engine modeling for a simulation that is physically based, captures the wave effects in the manifolds, treats cylinders individually and is suitable for running in real-time. This section describes an approach to modeling fluid transients in duct systems in combination with in-cylinder combustion models and avoiding computationally expensive functions.

Features of the model

Whilst the purpose of a 1-D simulation is to predict absolute values of engine performance in terms of volumetric efficiency, torque and fuel economy, the real-time (RT) model need only replicate these values to an agreed accuracy, while accurately preserving the transient behaviour. The model data is directly translated