Virtual GDI Engine as a Tool for Model-based Calibration

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Due to emissions regulation, engines are ever more complex.

Devices like:

- Turbocharger and/or supercharger (for downsizing)
- Swirl or Tumble Control Valve (SCV and TCV)
- EGR systems
- Direct Injection
- Multiple Injection strategies
- Variable Valve Timing and/or Actuation
- Hybridization Concepts
- …

Are possible ways to reduce both polluting emission and fuel consumption, but they introduce more degrees of freedom in engine calibration.
Introduction and objectives

The **objective** of this work is to demonstrate that virtual simulation can help engine developers to significantly reduce efforts to reach optimal engine control.

- When working to recalibrate a well-known engine (possibly due to components modifications), it’s possible to save time and cost, working on virtual simulation.

- When working to precalibrate a new engine, virtual engine pre-calibration can be carried out before real engine realization (working together with 3D simulation tools) avoiding hardware failures and supporting the engine development department.
Virtual Calibration Approach

First step is the realization of a fully predictive 1D engine model starting from geometrical data of the engine.

- To calibrate this model, experimental data can be used if the engine is not a new engine (e.g. in case of a new device added on an existing engine, or to improve current calibration, …). In case of a new engine, detailed 3D model simulation is the optimal way to calibrate 1D combustion model.

Second step is the model reduction, with the objective of minimizing computational time. The challenge in this operation is to make computational time reduction without sensible loss of results accuracy.

Then, a fast model may be used in place of the real engine, on the virtual test bench.

- Every kind of controls can be virtually added, and several pre-calibration, “standardized” tests can be carried out, without damage risks.

- On the other side, not all control domains may always be investigated in the virtual simulation environment.
  - For gasoline direct injection engines, current two-zones SI 1D combustion models aren’t able to deeply investigate multi-injection effects: in this case, multiple injection has to be calibrated on the test bench, or using 3D models.
The engine used in this test is a direct injection spark ignition engine with:

- Turbocharger
- Supercharger
- Tumble Control Valve (or Tumble Flap)
- Intake Variable Valve Timing (iVVT)

This engine is able to deliver almost 100kW per liter, with extremely low fuel consumption figures. This is possible only if all the available actuators are optimally managed.
1D complete engine model is a geometrically detailed representation of the real engine.

Main model characteristics:

- Full predictive CombSITurb combustion model
- Independent cylinders
- Wall temperature solver used on wall pipes
- SAE maps for supercharger and turbocharger (by supplier)
To reduce the computational effort of the engine model (1:10 simulation time reduction achieved), two main paths have been followed:

- Volumes merging, to reduce the number of equations to be solved
- Using a master-slave cylinder combustion model instead of independent ones
### 1D Engine Model

#### Engine Model Reduction

Experimental engine working points used to calibrate 1D full model and to validate 1D reduced model

<table>
<thead>
<tr>
<th>POINT</th>
<th>469</th>
<th>551</th>
<th>451</th>
<th>452</th>
<th>448</th>
<th>481</th>
<th>538</th>
<th>461</th>
<th>463</th>
<th>592</th>
<th>742</th>
<th>754</th>
<th>682</th>
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<tr>
<td>[rpm]</td>
<td>1750</td>
<td>3000</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
<td>2000</td>
<td>2750</td>
<td>1500</td>
<td>1500</td>
<td>3500</td>
<td>5500</td>
<td>5500</td>
<td>4500</td>
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<tr>
<td>Throttle [%]</td>
<td>13.3</td>
<td>8.9</td>
<td>9.2</td>
<td>11</td>
<td>5.2</td>
<td>6.7</td>
<td>16.4</td>
<td>100</td>
<td>100</td>
<td>18.9</td>
<td>20.4</td>
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<tr>
<td>Torque [Nm]</td>
<td>67.6</td>
<td>11.3</td>
<td>46.2</td>
<td>57.2</td>
<td>11.3</td>
<td>11.7</td>
<td>79.5</td>
<td>170.8</td>
<td>184.7</td>
<td>79.8</td>
<td>56.6</td>
<td>180.7</td>
<td>214.9</td>
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<td>VVT</td>
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<td>-15.2</td>
<td>-37.8</td>
<td>-39.4</td>
<td>-15.6</td>
<td>-21.3</td>
<td>-36.3</td>
<td>-12.8</td>
<td>-11.0</td>
<td>-29.3</td>
<td>-11.2</td>
<td>-10.3</td>
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<tr>
<td>supercharger</td>
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<td>off</td>
<td>ON</td>
<td>ON</td>
<td>off</td>
<td>off</td>
<td>off</td>
<td>off</td>
</tr>
<tr>
<td>tumble flap</td>
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<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>off</td>
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<td>WG</td>
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<td>off</td>
<td>off</td>
<td>off</td>
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</tbody>
</table>

In cylinder pressure (538):

- PCYL, EXP
- PCYL GT-P
- PCYL GT-P Reduced

In cylinder pressure (592):

- PCYL, EXP
- PCYL GT-P
- PCYL GT-P Reduced
While reducing the model, attention should be paid to heat exchange phenomena: differences may exist between geometrically detailed model and reduced model.

Fully automatic model reduction required manual correction of heat exchange parameters in intake and exhaust ducts.

This recalibration had negligible effects on in-cylinder pressure calculation.

In the graph, measured (EXP) versus modeled Turbine Inlet Temperature (fully 1D – GT-P, reduced, reduced with modified heat exchange coefficients – MOD COLL)
Aim: maximize output torque while respecting external constraints (limits)
An automatic control increases the SA to obtain the maximum efficiency. The control is related to a virtual knock sensor used to determine the best position of the SA.
VVT control is set to search the maximum cylinder filling, moving the valve timing inside VVT range.
Results

Full load validation

T and P: comparison between experimental results and virtual ones using experimental input parameters (same set of calibration parameters)
Results
Full load optimization

T and P: comparison between experimental results and virtual optimized engine (on the right)

Spark Advance and VVT optimized by virtual simulation vs applied ones on engine by original ECU
Aim: Minimize a cost function based on pollutant emissions, for each engine working point

As a demonstrative cost function, the normalized sum of the HC, CO, and NOx levels was assumed in this study.
Results

Emission Cycle Zone (1750 rpm, 17 Nm)

In this example, HC, CO, and NOx sensitivity to both VVT and tumble flap position has been investigated via the virtual engine model.
Results

Emission Cycle Zone (1750 rpm, 17 Nm)

This example shows VVT optimization on HC, CO, Nox, using tumble flap on and off.

The normalized sum (cost function), is a possible, basic index used to find the best compromise: weights can of course be different for each element (or normalized referring to regulated limits)
Conclusions

Main step for Engine pre calibration by 1D virtual simulation:

- Full predictive 1D engine model
- 1D engine model reduction
- Calibration methodology application on a fast 1D virtual engine

This case of study assesses that:

- It is possible to reduce experimental costs and risks generating a precalibration set of parameters by virtual simulation and use this set of parameters as starting point for fine tuning on engine test bench
- It is very important for developer engineers because it permits to increase sensitivity about engine control issues, and to deeply understand relationships between input parameters and output targets of the engine
- Semi-automatic model reduction may lead to inconsistent boundary conditions, or to non-realistic heat exchange coefficients values
Thank you for your attention