Digital Shaping and Optimization of Fuel Injection Pattern for a Common Rail Automotive Diesel Engine through Numerical Simulation

European GT Conference 2017 - Frankfurt am Main

Politecnico di Torino: Sapio, F., Piano, A., Millo, F.

General Motors GPS: Pesce, C. F.
Agenda

- Introduction
- Injector Modeling
- Combustion Modeling
- Injection Strategies Optimization
- Conclusions
- Ongoing Work
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Aim of the Work

Exploiting the **fuel injection pattern** and *shaping* potential in reducing **BSFC** and *combustion noise*, without exceeding the **target emissions level**, by means of a **virtual test-rig**.

<table>
<thead>
<tr>
<th>Engine type</th>
<th>DI Turbocharged Diesel EURO6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>1598 cm³</td>
</tr>
<tr>
<td>Bore × stroke</td>
<td>79.7 mm × 80.1 mm</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>16:1</td>
</tr>
<tr>
<td>Turbocharger</td>
<td>Single-stage with VGT</td>
</tr>
<tr>
<td>Fuel injection system</td>
<td>Common Rail</td>
</tr>
<tr>
<td>Maximum power and torque</td>
<td>100 kW @ 4000rpm 320 Nm @ 2000rpm</td>
</tr>
</tbody>
</table>

Source:

"Digital Shaping and Optimization of Fuel Injection Pattern for a Common Rail Automotive Diesel Engine through Numerical Simulation", Francesco SAPIO
Virtual Test Rig

Source: http://www.boschautoparts.com

"Digital Shaping and Optimization of Fuel Injection Pattern for a Common Rail Automotive Diesel Engine through Numerical Simulation", Francesco SAPI

09-10-2017
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Experimental Setup

In order to build a 1D-CFD model of a CR injector, 2 crucial issues need to be addressed.

- Internal geometry detection
- Extensive dataset of experimental injection rate
- 3D Computed Tomography
- STS Injection Analyzer

Source: [http://www.boschautoparts.com](http://www.boschautoparts.com)

"Digital Shaping and Optimization of Fuel Injection Pattern for a Common Rail Automotive Diesel Engine through Numerical Simulation", Francesco SAPIO

09-10-2017
Injector Model Results – EMI

Single Injections

Rail Pressure = 400 bar

Rail Pressure = 600 bar

Rail Pressure = 1000 bar

Rail Pressure = 1200 bar

EMI Curves

pRail = 400 bar

pRail = 600 bar

pRail = 1000 bar

pRail = 1200 bar

"Digital Shaping and Optimization of Fuel Injection Pattern for a Common Rail Automotive Diesel Engine through Numerical Simulation", Francesco SAPIO

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Injectors Model Results – IR

**Single\Double + Close Pilot**

**Rail Pressure = 400 bar**

**Rail Pressure = 1000 bar**

**3 Pilots + Main + After**

**Rail Pressure = 400 bar**

"Digital Shaping and Optimization of Fuel Injection Pattern for a Common Rail Automotive Diesel Engine through Numerical Simulation", Francesco SAPIO

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Injection Rate Map (IRM)

<table>
<thead>
<tr>
<th>Engine Model CPU Increase Factor due to adding Detailed Injection*</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Detailed injectors</td>
</tr>
<tr>
<td>1 Master injector + 3 slaves</td>
</tr>
<tr>
<td>Injection Rate Map</td>
</tr>
</tbody>
</table>

*Source: courtesy of Gamma Technologies

- **Advantages**
  - Best trade-off between accuracy and CPU time

- **Drawbacks**
  - Unable to detect pulse interaction

- **Inputs**
  - Injected Mass per Pulse or ET
  - Rail Pressure

- **Output**
  - Injection Rate (Interpolated)

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DI Pulse Combustion Model

- Predictive
- Multi-zone
  - Main Unburned Zone (MUZ)
  - Spray Burned Zone (SBZ)
  - Spray Unburned Zone (SUZ)
- Calibrated on 28 engine operating points

### DI Pulse Calibration Parameters*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entrainment Rate Multiplier</td>
<td>0.95 – 2.8</td>
</tr>
<tr>
<td>Ignition Delay Multiplier</td>
<td>0.3 – 1.7</td>
</tr>
<tr>
<td>Premixed Combustion Rate Multiplier</td>
<td>0.05 – 2.5</td>
</tr>
<tr>
<td>Diffusion Combustion Rate Multiplier</td>
<td>0.4 – 1.4</td>
</tr>
</tbody>
</table>


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DI Pulse Calibration Results

Pressure Measured  Pressure Predicted  Burn Rate Measured  Burn Rate Predicted  Injection Rate

1500 x 2

1500 x 5

2000 x 2

2000 x 8

1500 x 8

1500 x 12

3000 x 23

3500 x 21

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Engine map

Results in terms of main global indexes are shown, related to the whole engine map (337 operating points).

Good agreement with experimental data is obtained.

- Avg IMEP error < 5%
- Avg Pmax error < 5 bar
- Avg CA of Pmax error < 2 deg
- Avg CA of MFB50 error < 2 deg

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**DIPulse Calibration Results**

**Calibration points**

Results in terms of emissions are shown, related to the 28 chosen calibration points.

**EGR sweep points**

EGR sweep results in terms of NOx emissions are also shown, related to 7 PL engine operating points.

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Model Setup

Detailed Configuration

- 4 cylinder based
- Detailed intake/exhaust geometry
- Turbocharger
- EGR circuit

Advantages
- Accurate

Drawbacks
- Computationally expensive
Model Setup

Simplified Configuration (TPA)

- Single cylinder based
- Imposed intake/exhaust pressures and temperatures
- Imposed intake air residual fraction (EGR rate)
- Injection Rate Map
Simplified configuration achievements

- Similar results compared with the detailed model
- Lower computational time*

\[
\frac{1}{6}
\]

\*(CPU Intel® Xeon® E31245 @ 3.30GHz, 4 core)

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Combustion Noise in GT-SUITE

- **Evaluation procedure**
  - In-cylinder pressure signal is taken during the simulation
  - Cylinder Pressure FFT is performed
  - A-filter + CAVTAB-filter attenuation is introduced
  - Overall octave bands content in dB is evaluated

- **Validation**
  - Engine Map (337 operating points)

![Graph showing simulated vs. experimental combustion noise](image)
DoE Approach

Operating Key Points
- 1500 rpm x 2 bar
- 1500 rpm x 5 bar
- 2000 rpm x 8 bar

A DoE approach is adopted
1. Latin Hypercube – 20’000 experiments per case: exploration of the results space
2. Full Factorial – 500’000 experiments per case: starting from Latin Hypercube results, search refinement

Input Variables
- Number of Injections
- Energizing Time
- Dwell Time
- Rail Pressure
- Injection Timing (SOI Main)
- EGR Rate

Output Variables
- Brake Specific Fuel Consumption (BSFC)
- Brake Specific NOx (BSNOx)
- Combustion Noise (CN)
DoE Post Processing

Normalized Output Variables

| Normalized – BSFC      | BSFC  \\
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BSFC&lt;sub&gt;t&lt;/sub&gt;</td>
</tr>
</tbody>
</table>
| Normalized – BSNOx     | BSNO<sub>x</sub>  \\
|                        | BSNO<sub>x,t</sub> |
| Normalized – CN Factor | 10<sup>(dB−dB<sub>t</sub>)<sup>20</sup></sup> |

- Target emission level is set to the baseline value ± 5%

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Results – 1500x2 (RPMxBMEP)

<table>
<thead>
<tr>
<th>1500 x 2</th>
<th>N-BSFC</th>
<th>N-BSNOx</th>
<th>N-CNFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Pil</td>
<td>0.97</td>
<td>1.00</td>
<td>1.06</td>
</tr>
<tr>
<td>2 Pil</td>
<td>0.96</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>3 Pil</td>
<td>0.96</td>
<td>0.98</td>
<td>0.97</td>
</tr>
<tr>
<td>4 Pil</td>
<td>0.96</td>
<td>0.95</td>
<td>0.73</td>
</tr>
<tr>
<td>5 Pil</td>
<td>0.97</td>
<td>0.99</td>
<td>0.85</td>
</tr>
</tbody>
</table>

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Results – 1500x5 (RPMxBMEP)

<table>
<thead>
<tr>
<th>1500 x 5</th>
<th>N-BSFC</th>
<th>N-BSNOx</th>
<th>N-CNF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Pil</td>
<td>0.97</td>
<td>0.95</td>
<td>1.26</td>
</tr>
<tr>
<td>2 Pil</td>
<td>0.96</td>
<td>1.01</td>
<td>1.03</td>
</tr>
<tr>
<td>3 Pil</td>
<td>0.95</td>
<td>0.99</td>
<td>0.93</td>
</tr>
<tr>
<td>4 Pil</td>
<td>0.95</td>
<td>1.00</td>
<td>0.84</td>
</tr>
<tr>
<td>5 Pil</td>
<td>0.95</td>
<td>1.02</td>
<td>0.73</td>
</tr>
</tbody>
</table>
Results – 2000x8 (RPMxBMEP)

<table>
<thead>
<tr>
<th></th>
<th>N-BSFC</th>
<th>N-BSNOx</th>
<th>N-CNF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Pil</td>
<td>0.97</td>
<td>0.99</td>
<td>1.10</td>
</tr>
<tr>
<td>2 Pil</td>
<td>0.96</td>
<td>1.05</td>
<td>0.85</td>
</tr>
<tr>
<td>3 Pil</td>
<td>0.96</td>
<td>0.96</td>
<td>0.90</td>
</tr>
<tr>
<td>4 Pil</td>
<td>0.97</td>
<td>0.95</td>
<td>0.79</td>
</tr>
<tr>
<td>5 Pil</td>
<td>0.98</td>
<td>0.98</td>
<td>0.80</td>
</tr>
</tbody>
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Conclusions

Injection Strategies Optimization

A methodology for developing a 1D-CFD virtual engine test rig was presented. The virtual test rig includes the injection system model, the engine model with a calibrated predictive combustion model and the innovative control strategy of the ECU for the injection pattern. A large number of fuel injection patterns were tested and the best ones in terms of BSFC and CN reduction, without exceeding the target NOx emissions level, were selected. Some common trends can be highlighted at the end of this work:

- Compact multi-injection patterns
- High Rail Pressure
- Short Dwell Times
- Progressive Burn Rate

Achievements: improvements in BSFC up to 5%, CNF up to 30%, without exceeding in NOx emissions
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Multi-Objective – Results (1500x5)

Engine Operating Point – 1500 X 5

Complete Dataset
Cases tested by the optimization process in GT-SUITE

Constrained Dataset
BSNOx Constraint added on the complete dataset

Baseline
Baseline injection pattern configuration

The RED area represents the usable area where:

\[ BSFC_{actual} \leq BSFC_{baseline} \land CN_{actual} \leq CN_{baseline} \]
Multi-Objective – Resume

By means of GA is possible to reduce computational time of about 2 orders of magnitude with respect to a Full Factorial DoE approach.
Acknowledgements

➢ Prof. Federico MILLO
➢ Eng. Andrea PIANO
➢ Dr. Francesco C. PESCE
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