Single- and Multi-Objective Injection Strategy Optimizations by means of Genetic Algorithm

European GT Conference 2018
October 8th, 2018 – Frankfurt, Germany

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A. PIANO – Single- and Multi-Objective Injection Strategy Optimizations by means of Genetic Algorithm
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FIS optimization on Diesel Engine

**Aim**: optimization analysis of the injection parameters in order to fully exploit the potential of innovative FIS in terms of fuel consumption and combustion noise minimization, without exceeding the baseline NOx level.

Development trends in modern Common Rail FIS show dramatically increasing capabilities in terms of:

- **number of injection events** per engine cycle;
- **Rail pressure** increment;
- **Dwell Time** reduction;
- **modulation** and shaping of the injection rate.

<table>
<thead>
<tr>
<th>Engine Speed</th>
<th>BMEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPM</td>
<td>bar</td>
</tr>
<tr>
<td>1500</td>
<td>2.0</td>
</tr>
<tr>
<td>1500</td>
<td>5.0</td>
</tr>
<tr>
<td>2000</td>
<td>8.0</td>
</tr>
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</table>

Source: DELPHI, 2015
Virtual test rig

Reduced engine model configuration is needed for fuel injection pattern optimization since the detailed configuration requires a not suitable CPU time for simulations characterized by a large number of cases.
A injector control was built in GT-SUITE for the injection pattern definition. It consist of both injection timing and number controllers and works within the predefined Injection Rate Map.

A proper user subroutine was developed and validated over a large set of experimental data for combustion noise evaluation (average error that lies within ± 0.3 dB band).

A control unit able to manage engine load, MFB50 position, was implemented into the model.
Injector + Engine Coupling

In GT-SUITE environment, several options for injection and engine models integration.

1. **Slave injectors** – injection rate from only one injector model, copied and shifted based on firing order
2. **Skip cycle** – injector model runs for one cycle
3. **Partial cycle** – injector model runs only in a part of the engine cycle when injection appears
4. **Injection Rate Map (IRM)** – map of single injection profiles. In case of multiple injections, each pulse is looked up independently, without capturing pulse-to-pulse interaction.
Virtual test rig – Reduced Configuration

With this configuration, **significant improvements in computational time** were obtained while **maintaining a satisfactory agreement** with the previously validated detailed model results.

The average **CPU time** required to the detailed model in order to run the 3 key-points was **reduced of an order of magnitude** with the simplified configuration.
Virtual Test Rig

Trade-off
BSFC - BSNOx

Trade-off
BSFC - CN

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FIS optimization process

**PreProcess**
Input Variables Definition

**Process**
Optimization Strategies

**PostProcess**
Output Variables Definition
FIS optimization process

PreProcess
Input Variables
Definition

Process
Optimization
Strategies

PostProcess
Output Variables
Definition

<table>
<thead>
<tr>
<th>Parameter name</th>
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</tr>
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<tbody>
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<td></td>
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<td>-</td>
<td>1</td>
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<tr>
<td></td>
<td></td>
<td>6</td>
</tr>
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Number of injection events

![Graph showing Injection Rate vs. Crank Angle]
FIS optimization process

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<tr>
<td>Number of injection events</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Injected mass</td>
<td>mg</td>
<td>0.4</td>
</tr>
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</table>

- Injected mass
- Injected mass

Crank Angle [deg]
Injection Rate [L]

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October 8th, 2018

11
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<tr>
<td>Dwell time</td>
<td>ms</td>
<td>0.0</td>
</tr>
<tr>
<td>Rail pressure</td>
<td>bar</td>
<td>200</td>
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</tr>
<tr>
<td>Injected mass</td>
<td>$mg$</td>
<td>0.4</td>
</tr>
<tr>
<td>Dwell time</td>
<td>$ms$</td>
<td>0.0</td>
</tr>
<tr>
<td>Rail pressure</td>
<td>$bar$</td>
<td>200</td>
</tr>
<tr>
<td>Delta SOI Main (wrt baseline)</td>
<td>$deg$</td>
<td>- 4.0</td>
</tr>
</tbody>
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FIS optimization process

PreProcess
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Process
Optimization Strategies

PostProcess
Output Variables Definition

Parameter name | Minimum value | Maximum value
--- | --- | ---
Number of injection events | - | 6
Injected mass | mg | 0.4 | 1.5
Dwell time | ms | 0.0 | 3.0
Rail pressure | bar | 200 | 2000
Delta SOI Main (wrt baseline) | deg | -4.0 | +4.0
EGR rate | fraction | 0.0 | 0.5
FIS optimization process

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Full Factorial DoE
- Definition of a complete space of results
- High CPU time requested

Single-Objective
- Lower CPU time requested
- Definition of a representative objective function

Multi-Objective
- Lower CPU time requested
- High complexity with non-linear problems
The results of the analysis were normalized with respect to the baseline values, by the definition of the following 3 factors:

- **BSFC factor**
  \[ f_{BSFC} = \frac{BSFC_{\text{optimized}}}{BSFC_{\text{baseline}}} \]

- **BSNOx factor**
  \[ f_{BSNOx} = \frac{BSNOx_{\text{optimized}}}{BSNOx_{\text{baseline}}} \]

- **Combustion noise factor**
  \[ f_{CN} = 10^{\frac{(dB_{\text{optimized}}-dB_{\text{baseline}})}{20}} \]
Single-Objective analysis

An **Objective Function** $f(x)$ can be easily defined as:

$$f(x) = f(G(x))$$

- $x$ is the independent variable
- $G$ is the dependent variable

In this analysis, a modified version of Mallamo and Millo Objective Function was proposed:

$$f(x) = k_1 \frac{BSFC}{BSFC_{baseline}} + k_2 \cdot 10^{\left(\frac{dB-dB_{baseline}}{20}\right)} = k_1 f_{BSFC} + k_2 k_{CN}$$

The term $f_{BSNOx}$ was added as a **constraint**:

$$0.95 \leq f_{BSNOx} \leq 1.05$$

The **algorithm NSGA-III** was used for the analysis since it is optimized for strongly non-linear problems, the setting of which are briefly summarized as follows.

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<td>50</td>
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<td>Number of generations</td>
<td>100</td>
</tr>
<tr>
<td>Crossover rate</td>
<td>1</td>
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<td>Mutation rate</td>
<td>0.091</td>
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At the end of 5000 iterations, the Objective Function resulted minimized respect to the baseline value for the 3 analyzed engine points:

- the optimized strategies are characterized by an higher number of injection events with very short dwell time allowing a smoother pressure trace, thus reducing the combustion noise.

1500 RPM X 2 bar BMEP

1500 RPM X 5 bar BMEP

2000 RPM X 8 bar BMEP
Single-Objective analysis – Results

1500 RPM X 2 bar BMEP

1500 RPM X 5 bar BMEP

2000 RPM X 8 bar BMEP

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Multi-Objective analysis

Differently from the Single-Objective study, in the Multi-Objective approach the optimizer takes into account multiple dependent variables that can be simultaneously minimized or maximized.

By means of **Pareto front**, it is possible to see the results in a space defined by 2 (or even more) dependent variables. Pareto front is not an optimal point that minimizes/maximizes an objective function, but it is a continuum with several solutions that are considered to be equally good, without any other information.

The algorithm NSGA-III was used for the analysis since it is optimized for strongly non-linear problems. The **optimization settings are equal to the ones used in the Single-Objective analysis**.

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Multi-Objective analysis – Results

The complete iteration results can be highlighted in the BSFC-CN space, where the GA found solutions that improve the baseline results, both in terms of BSFC and CN.

- Similar trend with respect to the previous approaches can be highlighted.

1500 RPM X 2 bar BMEP

1500 RPM X 5 bar BMEP

2000 RPM X 8 bar BMEP
Multi-Objective analysis – Results

1500 RPM X 2 bar BMEP

Pressure [bar]

Burn Rate [1/deg]

Injection Rate [-]

Crank Angle [deg]

1500 RPM X 5 bar BMEP

Pressure [bar]

Burn Rate [1/deg]

Injection Rate [-]

Crank Angle [deg]

2000 RPM X 8 bar BMEP

Pressure [bar]

Burn Rate [1/deg]

Injection Rate [-]

Crank Angle [deg]
Conclusions 1/2

- A numerical optimization analysis aiming to minimize BSFC and Combustion Noise without exceeding the BSNOx baseline value, was presented for 3 engine operating conditions.

- BSFC improvement up to 7%, and significant combustion noise reduction could be achieved.
Conclusions 2/2

- Significant reduction in terms of requested CPU time.

The requested computational time has been reduced of 2 orders of magnitude adopting the GA based optimizer instead of the Factorial DoE approach (where 22 seconds are considered as the average value of the required time for a single simulation run).

The CPU time is referred to simulations distributed on a single core, Intel® Core™ i7-6700 3.4 GHz processor. *

* As a matter of fact, in these analysis, computations were parallelized on multiple cores, in order to reduce the total computational time by a factor equal to 1/n, where n is the total number of cores.
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