TC tools and matching process for a gasoline VTG/Miller concept

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Combination of Miller and variable turbine geometry for gasoline engines reduces knock tendency with high boost pressure provided by VGT

- For future emission regulation the complete engine map is relevant under all conditions
  - Reducing scavenging gas exchange at low-end-torque
  - Avoid enrichment at high engine speeds and loads

**Miller valve timings**
- Reduced knock tendency
- Lower exhaust temperatures
- Higher efficiencies

**Variable turbine geometry**
- Reduced back pressure
- Provide high boost pressure
- Improved transient performance
Agenda

- Motivation of the combination of Miller and VGT for gasoline engines
- Matching process and tools
- 1D-Gas exchange simulations
- Summary & Conclusion
Key elements for TC matching with 1D simulations for reliable and predictive results

Extended Turbine Mapping

TC friction test bench

TC inertia test bench

Matching process

Data post-processing

Extrapolated operating range

FEV TCTOOLS

TC testing

TC matching

Red. turbine mass flow

Aerodynamic efficiency

Turbine pressure ratio

Red. turbine mass flow

Aerodynamic efficiency

Turbine pressure ratio

Red. turbine mass flow

Aerodynamic efficiency

Turbine pressure ratio

Step 1: Rated power

Step 2: Low end torque

Step 3: Transient loadstep

Detailed measurements
FEV process overview for advanced turbocharger matching
Predictive TC simulation is the key to best in class engine performance

Online TC Scaling

Turbocharger Model

Engine Model

Aerodynamics

Bearing Friction Model

Heat Transfer

FEV Advanced Turbocharger Matching

3D CFD Simulation

3D Bearing Simulation

3D CHT TC Simulation

Hot Gas Measurements

Bearing Measurements

FEV Turbocharger Database

Open Loop

Closed Loop

Friction

Inertia

FEV Maps

TC Supplier DB
FEV process overview for advanced turbocharger matching
Modeling the aerodynamics
# FEV TC Tools

## Methodology Overview

<table>
<thead>
<tr>
<th>TC efficiency separation</th>
<th>Compressor and turbine scaling</th>
<th>Physical extrapolation model</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Separation of</td>
<td>- Scaling of overall size and</td>
<td>- Physically based</td>
</tr>
<tr>
<td>- Aerodynamics</td>
<td>trim</td>
<td>extrapolation of turbine</td>
</tr>
<tr>
<td>- Heat transfer</td>
<td>- Turbine housing scaling</td>
<td>- mass flow rate</td>
</tr>
<tr>
<td>- Friction</td>
<td>- Effect on efficiency and</td>
<td>- efficiency</td>
</tr>
<tr>
<td></td>
<td>flow characteristic</td>
<td>- Combined extrapolation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>of complete VGT maps</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Export to GT-POWER</td>
</tr>
</tbody>
</table>

### Workflow: Two software settings: “Fully automated” and “In-depth expert mode”

Results of hot gas measurements

Scaled TC maps or fully prepared GT-Model

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Procedure for scaling the turbine or compressor wheel (machine size) with one parameter to scale flow capacity, efficiency and speed.

- Empirical scaling of flow capacity and efficiencies based on scatter band data.
- Speed scaled according to fundamental laws of aerodynamic similarity.
- Online scaling in GT-POWER through use of mass and efficiency multipliers.
- Scaling factor can either be imposed or controlled to meet target value.

Remarks

Variation of turbine wheel (= machine) size:

- Empirical scaling of flow capacity and efficiencies based on scatter band data.
- Speed scaled according to fundamental laws of aerodynamic similarity.
- Online scaling in GT-POWER through use of mass and efficiency multipliers.
- Scaling factor can either be imposed or controlled to meet target value.
TC matching methodology
The DoE approach includes all matching relevant parameters

Target: Find minimum compressor and turbine size to fulfill rated power targets and boundary conditions

Approach: Joint optimization of TC size and valve lift profiles

Process description and boundary conditions

Compressor size
Turbine size
Valve events and timings and event

Step 1: Rated power

Step 2: Low end torque

Step 3: Transient load step
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Engine specifications and performance targets
Increased compression ratio enabled by Miller allows 90 kW/l

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>l</td>
<td>1.5</td>
</tr>
<tr>
<td>Cylinder number</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>-</td>
<td>11.4</td>
</tr>
<tr>
<td>Bore/stroke</td>
<td>-</td>
<td>82 / 94.6</td>
</tr>
<tr>
<td>Max. torque</td>
<td>Nm</td>
<td>260 @ 1500 1/min (BMEP = 22 bar)</td>
</tr>
<tr>
<td>Max. power</td>
<td>kW</td>
<td>135 @ 5500 1/min → 90 kW/l</td>
</tr>
<tr>
<td>Max. Miller ratio*</td>
<td>-</td>
<td>1.23</td>
</tr>
</tbody>
</table>

Miller ratio = \( \frac{V_H, \text{ expansion}}{V_H, \text{ compression, effective}} \)

*with earliest IVO = 20 °CA bTDC (ref. 1 mm lift)
Compressor with high pressure ratio required for Miller at rated power

HONEYWELL COMPRESSOR MEASURED ON FEV HOT GAS TEST BENCH

Description
- TC matching done with a HTT compressor measured on FEV hot gas test bench
Compressor with high pressure ratio required for Miller at rated power
VGT provides higher boost pressures than WG turbine

HONEYWELL COMPRESSOR MEASURED ON FEV HOT GAS TEST BENCH

TC matching done with a HTT compressor measured on FEV hot gas test bench

High boost pressure required at rated power (RP)

FEV matching process considering
- valve timing optimization
- turbine size
- compressor size
Turbine evaluation with FEV scatterband
VGT shows higher turbine efficiency compared to WG turbine

**FEV TURBOCHARGER SCATTERBAND TO ASSESS TURBINE PEAK EFFICIENCY**

- A Honeywell turbine with high turbine efficiency has been selected
- VGT turbines show higher turbine efficiency due to guide vanes
- The maximum efficiency of the wastegate turbine is approx. 2% lower in comparison to the VGT
- Same turbine wheel size → same rotor inertia
VGT achieves 90 kW/l with high Miller ratio, $\lambda=1$ and low fuel consumption

SIMULATION RESULTS AT ENGINE FULL LOAD OPERATION RATED POWER 5500 RPM

- Wastegate and VGT both reach power target of 90 kW/l
- Reduced pumping work with VGT
- Max. 950 °C upstream turbine
- VGT enables higher Miller ratio
  - Advanced combustion phasing
  - Reduced enrichment
  - Reduced fuel consumption

<table>
<thead>
<tr>
<th>Miller ratio</th>
<th>PMEP / bar</th>
<th>Spec. fuel consumption / g/kWh</th>
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<tbody>
<tr>
<td>WG</td>
<td>VGT</td>
<td></td>
</tr>
<tr>
<td>1</td>
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<td>1,04</td>
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<td>1,08</td>
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<td>1,16</td>
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</table>

<table>
<thead>
<tr>
<th>Spec. air-fuel ratio</th>
<th>Spec. fuel consumption / g/kWh</th>
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<tbody>
<tr>
<td>0,9</td>
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<td>0,92</td>
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<td>0,94</td>
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<td>0,96</td>
<td></td>
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<tr>
<td>0,98</td>
<td></td>
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<td>1</td>
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</tbody>
</table>

Results

- $\approx -19\%$
- $\approx -11\%$
Closing the VGT position at low engine speeds enables 22 bar BMEP with Miller valve timings

SIMULATION RESULTS AT ENGINE FULL LOAD OPERATION LOW-END-TORQUE 1500 RPM  BMEP = 22 BAR

- WG turbine has a flow capacity equal to 60 % VGT position
  - At Low-End-Torque the VGT offers margin to further reduce flow capacity
  - Higher boost pressure achievable
- Both concepts achieve BMEP
- VGT achieves higher Miller ratio with constant load
  - Reduced fuel consumption

Measured turbine maps are post processed with FEV’s TC Tools software
20 % VGT-position shows best transient performance

VGT -POSITION VARIATION FOR A LOAD STEP AT 1500 RPM

Results

- Load steps starting from 2 bar BMEP have been performed at 1500 rpm
20 % VGT-position shows best transient performance

Load steps starting from 2 bar BMEP have been performed at 1500 rpm

Closing the VGT leads to an increased turbine pressure ratio and higher turbine power

→ Faster transient performance

At very low VGT positions the high turbine back pressure leads to an increased pumping work and high in-cylinder residual gas fraction

→ Best VGT position = 20 %
VGT shows a 48 % reduced Time-To-torque

**Results**

- The wastegate of the WG turbine is closed after start of load step
VGT shows a 48 % reduced Time-To-torque

COMPARISON OF THE TRANSIENT ENGINE PERFORMANCE AT 1500 RPM

- The wastegate of the WG turbine is closed after start of load step
- The same rotor inertia is applied due to the same wheel size
- The VGT enables an acceptable transient performance for Miller engines

→ Time-To-Torque of the VGT is reduced by - 48 % in relation to the wastegate turbine
Agenda

- Motivation of the combination of Miller and VGT for gasoline engines
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Summary & Conclusion

- FEV TCTOOLS provides a physical based extrapolation of the TC hot gas measurements
- Online scaling function in GT-POWER enables an efficient matching process
- The compressor needs to be matched with respect to Miller requirements
- The investigated 90 kW/l 1.5L engine shows
  - -11 % BSFC at rated power with \( \lambda = 1 \)
  - -2 % BSFC at Low-End-Torque
- Significantly reduced Time-To-Torque -48 % with VGT turbine
Acknowledgement

The authors would like to thank:

Honeywell
THE POWER OF CONNECTED

Thank you for your Attention!