PERFORMANCE AND ACOUSTIC MULTI-OBJECTIVE OPTIMIZATION ON A 2-CYLINDER MOTORCYCLE ENGINE: METHODOLOGY AND CASE STUDY

Francesco Maiani, Nicola Salvatelli, Alessandro Ciacci
Piaggio & C. S.p.A.
Contents

• Project overview

• Optimization procedure: structure
  – Combined simulation GT-SUITE® – modeFRONTIER®

• Results
  – Final vs baseline configuration

• Conclusions
Today's challenge and common issue

- Environmental impact
  - Increase the overall engine efficiency
  - Meet the Euro 4 exhaust noise levels
- The use of numerical models and calculation methodologies provides an important support in pursuing this goal
Objective

• To build a new automated and integrated methodology focused on:
  
  – Exhaust line design
    • Focusing on engine performance and sound pressure levels
    • Within the style and design constraints
  
  – Valve lift event design
    • According to kinematic and dynamic indicators of control and durability of the valve train system
    • Focusing on engine breathing

... in order to reach a performance / acoustic trade-off
Application and Engine specifications

• Piaggio motorcycle engine
  – 2-Cylinder SI 4-strokes
  – PFI injection
  – Water cooled
  – DOHC direct arrangement

• Particular attention paid to engine performance and SPL reduction, by means of:
  – Exhaust manifolds and muffler geometry
  – Valve lift event

• This becomes decisive to provide a competitive vehicle for motorcycle market (Euro 4)
Pass-by test (Euro 4)

- Classification parameter: PMR
  - PMR (Power Mass Ratio) = \( \frac{P_n}{m_t} \) [W/kg], where:
    - \( P_n \) [W] = max power
    - \( m_t \) [kg] = vehicle + driver mass

- Test cases: max acceleration and constant speed

- SPL measured < SPL limit
  - Limit based on PMR
Workflow

- The multi-objective platform (modeFRONTIER®) plays a key-role driving the calculation software (GT-SUITE®) used for engine performance and valve train system evaluation.
Optimization methodology

Structure

Flowchart

Start

Exhaust pipes and muffler geometry; valve lift event design

Run engine performance model

Run valve train model

No

Yes

Engine response meet target acoustic and performance?

Change parameters within a certain range

Valve train parameters meet guidelines?

No

Both conditions are met?

No

Yes

Optimization loop

Finish

Optimized geometry and profiles to choose from
Exhaust line design

- Exhaust manifolds
  - Pipe diameters and lengths
- Muffler geometry
  - Pipe diameters, lengths, and baffle locations

<table>
<thead>
<tr>
<th>Input variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1, D2, D3</td>
<td>Diameters of internal muffler pipes</td>
</tr>
<tr>
<td>X1, X2</td>
<td>Axial locations of muffler baffles</td>
</tr>
<tr>
<td>L_prim1, L_prim2, L_second</td>
<td>Lengths of exhaust pipes</td>
</tr>
<tr>
<td>fi_1, fi_2, fi_second</td>
<td>Diameters of exhaust pipes</td>
</tr>
</tbody>
</table>
Cam profile design procedure

- Multiple polynomial technique for valve lift definition
  - Template of GT-SUITE® used
  - Cam profile acceleration defined by 6 opening and 6 closing 5th order polynomials
- Acceleration continuity condition between each segment
- Based on the use of 4 shape parameters to define jerk in each junction point

<table>
<thead>
<tr>
<th>Input variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>θ₁ θ₂ θ₃ θ₅ θ₆</td>
<td>Angular durations for each zone of half-cam profile acceleration</td>
</tr>
<tr>
<td>f₁ f₂ f₃ f₄</td>
<td>Non-dimensional shape parameters</td>
</tr>
<tr>
<td>H_max</td>
<td>Maximum valve lift event</td>
</tr>
<tr>
<td>Timing anchor</td>
<td>Crank timing angle</td>
</tr>
</tbody>
</table>
Previous works experience

Design choices

• Experience gained in terms of significance and sensitivity of many input variables has allowed to save time bypassing some phases of the analysis (statistical analysis and DOE sequences)

• Some input variables have been considered as constant values (low correlation)
  – Evaluated only the exhaust valve lift event
  • Excel spreadsheet to calculate the min. valve-piston distance

• Simplified engine modeling (geometry and number of engine speeds) in order to make more straightforward the entire process

... from previous investigations ...
GT-POWER® (performance)

• Input parameters
  – Exhaust manifolds and muffler geometry
  – Valve lift profile
• Output parameters
  – Torque and power curves
  – SPL curve
• Microphone location: 7.5 m from tail pipe

Engine modeling

Engine torque and power (experimental validation)
GT-POWER® (acoustic)
- Input parameters GEM3D®
  - Muffler geometry

Transfer impedance
(experimental validation)
Optimization methodology
Engine modeling

GEM3D®
• Geometry parameters ➔ Automatic mesh

Independent parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Description</th>
<th>Case 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case On/Off</td>
<td></td>
<td>Check Box to Turn</td>
<td></td>
</tr>
<tr>
<td>Case Label</td>
<td></td>
<td>Unique Text for Plot</td>
<td></td>
</tr>
<tr>
<td>x1</td>
<td>mm</td>
<td>Location along Shell</td>
<td></td>
</tr>
<tr>
<td>x2</td>
<td>mm</td>
<td>Location along Shell</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>mm</td>
<td>Diameter</td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td>mm</td>
<td>Diameter</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dependent parameters

Config. n

Config. n+1
GT-SUITE®

- Input parameters
  - Multiple-Polynomial valve lift curve

- Output parameters
  - Kinematic and dynamic parameters to achieve the required functional and mechanical behavior

Direct overhead cam–tappet arrangement
Optimization objectives and constraints

- Objectives
  - Engine power @ max power speed
  - Engine torque @ max torque speed

- Constraints (criteria to meet)
  - Valve-piston distance
  - Cam-follower separation speed
  - Hertzian stress
  - Max cam torque
  - Valve seating velocity
  - Lubrication conditions
  - Target noise level
  - Target power curve
Optimization methodology
Followed approach

Optimization procedure: approach

• Statistical analysis
  – Not performed thanks to previous experience

• Optimization analysis
  – MOGA II genetic algorithm
    • Trade-off for the No. of starting population and the No. of Generations
      focused to increase robustness, accuracy and CPU time

Logical flow
Optimization methodology
Run data

Run Analysis
- About 1600 designs evaluated (2100 estimated)
- 36 feasible designs (about 2.3%)
  - Small number of feasible design due to strictly constrained problem formulation
  - 4 designs lying on Pareto frontier

Run times
- CFD-1D simulation time about 4’ (GEM embedded)
- V-Train simulation time about 2.5’
- modeFRONTIER optimization time about 50 hours
  - Time saving by using 4 concurrent processes and Synchronizer Nodes
Optimization methodology

Results

Post-processing results

- Correlation Matrix chart
  - Correlation values between the variables
- t-Student Distribution chart
  - Sensitivity analysis

<table>
<thead>
<tr>
<th>Input variable</th>
<th>How much affects the output</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_1$</td>
<td>Medium/Low correlation</td>
</tr>
<tr>
<td>$\varphi_1$</td>
<td>Medium/Low correlation</td>
</tr>
<tr>
<td>$\theta_3$</td>
<td>Medium/High correlation</td>
</tr>
<tr>
<td>$\varphi_3$</td>
<td>Medium/High correlation</td>
</tr>
<tr>
<td>$D_2$</td>
<td>Medium/High correlation</td>
</tr>
<tr>
<td>$D_3$</td>
<td>Medium/High correlation</td>
</tr>
<tr>
<td>$X_2$</td>
<td>Medium/High correlation</td>
</tr>
<tr>
<td>Anc_A</td>
<td>Medium/High correlation</td>
</tr>
<tr>
<td>Anc_S</td>
<td>Medium/High correlation</td>
</tr>
</tbody>
</table>
Optimization methodology

Results

Post-processing results

- Parallel Coordinates chart
  - Most promising solutions
- Bubble chart and Pareto Frontier
Muffler geometry

- Baseline

- Optimal

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Final vs Baseline</th>
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</thead>
<tbody>
<tr>
<td>Vol_chamber I</td>
<td>+ 85 %</td>
</tr>
<tr>
<td>Vol_chamber II</td>
<td>- 21 %</td>
</tr>
<tr>
<td>Vol_chamber III</td>
<td>- 41 %</td>
</tr>
<tr>
<td>φ in-muffler pipe</td>
<td>+ 1.9 %</td>
</tr>
<tr>
<td>φ pipe I-II</td>
<td>- 6.9 %</td>
</tr>
<tr>
<td>φ pipe II-III</td>
<td>- 5.0 %</td>
</tr>
<tr>
<td>φ tailpipe</td>
<td>- 8.6 %</td>
</tr>
</tbody>
</table>

Optimization methodology
Best design
Impact on performance

• Power curve
  – Slight worsening due to rigid and conflicting outputs
  • Making the thermodynamic objective the top-priority could have been another way to go (modular approach)

• SPL curve
  – Noise radiated from the exhaust tailpipe
  – 3 % reduction compared to baseline configuration (@ 3000 RPM)
  • Allowing Euro4 homologation

Optimization methodology
Best design
Impact on valvetrain
- Optimized valve diagrams
  - Parameters under control

<table>
<thead>
<tr>
<th>ValveTrain characteristics</th>
<th>Improvement %</th>
<th>Meet guidelines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min valve-piston distance Exhaust</td>
<td>25%</td>
<td>Yes</td>
</tr>
<tr>
<td>Min valve-piston distance Intake</td>
<td>8%</td>
<td>Yes</td>
</tr>
<tr>
<td>Cam-follower sep. speed</td>
<td>5%</td>
<td>/</td>
</tr>
<tr>
<td>Peak cam torque at overspeed</td>
<td>-10%</td>
<td>/</td>
</tr>
<tr>
<td>Max Hertz stress at 0RPM</td>
<td>-5%</td>
<td>Yes</td>
</tr>
<tr>
<td>Valve seating velocity</td>
<td>8%</td>
<td>Yes</td>
</tr>
<tr>
<td>Lubrication Number</td>
<td>-6%</td>
<td>Yes</td>
</tr>
<tr>
<td>Derivative of lubrication entrainment velocity</td>
<td>-24%</td>
<td>Yes</td>
</tr>
<tr>
<td>Cam/tappet contact area (max tappet velocity)</td>
<td>-3%</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Optimization methodology

Strengths

• Automated procedure to define and optimize engine parameters
  – Involving both engine and timing system response
  – Opportunity to avoid time-consuming jobs oriented to modify manually in closed loop pipes and muffler geometry and lift event
  – Exploitable in different stages of engine development
    • For a first investigation or in support of optimization or refinement analysis
• Sensitivity and decision support tool
  – Easy and automated way to investigate how design parameters affect the output results
• Modular approach adaptable on the basis of user targets and needs
  – The analyst can assign a priority to each objective
Conclusions

• A new integrated and automated multi-objective optimization methodology has been developed
  – Focusing on engine breathing, noise levels and timing system response
  – The effectiveness of this numerical procedure has been explored and exploited during the development of the new Piaggio motorcycle gasoline engine
• In particular the engine SPL has been improved using this methodology preserving the engine performance and involving a new exhaust system layout and a new cam design
  – The multi-objective optimization platform (modeFRONTIER) has allowed to combine the engine performance and the valve train models (GT-POWER / GEM3D / GT-SUITE)
Thank you for your attention

Contact information

Francesco Maiani
Piaggio & C. s.p.a.
Viale Rinaldo Piaggio, 25, 56025, Pontedera (Pisa), Italy
E-mail francesco.maiani@piaggio.com
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