Model Based Engine Calibration
Using State of the Art Software Support

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Introduction

• Model based calibration
  – Use of models of the engine behavior for main calibration
  – Models are created using Design of Experiments (DoE) Methods
• DoE in engine development is more than just experiment design
  – It is a synonym for a structured methodology of calibration
• Split nature of the process
  – Statistical knowledge for analysis
  – Test cell automation for data gathering
• Typical end user understands engines / calibration
  – But is not a statistics expert
  – Does not specialize in test bed control systems
Objective

- Objective
  - Demonstrate how to use the software tools to execute a typical calibration task
  - Ease of use
- Calibration Goal
  - Optimize part of the speed/relative load map of a gasoline engine
- Definition of Factors
  - Define optimal settings for available parameters
    - Variable Valve Timing
    - Spark Advance
    - Lambda
- Optimization Objectives
  - Minimize brake specific fuel consumption (BSFC)
  - Minimize the BSFC and emissions
  - Maximize the torque
State of the Art Software Tools

- The use of state of the art software tools facilitates the process for the end user and organization
  - EasyDoE ToolSuite provides statistical methods
  - ORION provides procedures for automated testing
**Definition of Factors and Responses**

- The factors required are
  - Engine Speed
  - Relative Load
  - Variable Valve Timing
  - Spark Advance
  - Lambda

- Optimization Constraints
  - Spark advance less than or equal to MBT Spark

- Monitor during data gathering
  - Knock Amplitude
  - Water, Oil Temperatures, etc.

- The responses required are
  - Torque
  - Mass Fuel Flow
  - Exhaust Temperature
  - Maximum Brake Torque (MBT)
  - Spark
  - Emissions HC/CO/NOx
  - Coefficient of Variation of Indicated Mean Effective Pressure (COV of IMEP)
  - BSFC (calculated)

\[
R = f(Spd, Ld, VVT, Spk, Lmd) \\
MBT = f(Spd, Ld, VVT, Lmd)
\]
Set Up Project

- Factors and responses are entered into EasyDoE Toolsuite
EasyDoE Test Plan

- The experiment design is entered, and 145 points are generated.
A&D Technology’s R&D Test Cell

Test Cell Features:
- ORION Test Automation
- iTesT Bench control
- ADX rapid prototype ECU
- Best Sokki Emissions Bench
- CAS Combustion Analysis

Engine Features:
- Production 4-cyl gasoline engine
- Variable Valve Timing
ORION Configuration

- ORION MDA is the key interface for the user creating the configuration.
- Main configuration task is Compiling the following elements:
  - Parameters – both from the test cell and Calibration tool.
  - Sequence – action to be executed in, flow-chart based.
  - Test Plan – all values from the DoE that the sequence needs to execute imported from Easy DoE.
ORION Test Execution

- MA is the key interface for the operator in the test cell
  - Simple load the configuration file from MDA
  - Connect to test cell control and calibration tool
  - Execute sequence by pressing “start”
- Indicators and graphs keep the operator informed on progress and status
- Test cell system collects the data as directed by MA via ORION “Measure” action
- MA remembers state of test point – measured successfully
  - Easy to restart a test
Data Gathering Strategy

- Save existing cal values
- Set speed and load
- Set VVT
- Set Lambda
- Sweep spark for MBT
  - Measure
- Set offset spark value relative to MBT Spark
  - Measure
- Reset cal values

Limit of:
COV of IMEP
Exhaust Temperature

Limit of:
COV of IMEP
Knocking Limit

1. Find MBT
2. Set Spark Timing Offset relative to MBT
   (value given by test plan)
Data Gathering Strategy

• Test cell run in speed / load mode

• Parallel control on spark advance during setting of speed / load and stepwise setting of VVT and Lambda
  – CA50
  – Monitored limits of temperature and knock

• Two data points taken for each Speed/Load/VVT/Lambda
  – On-line determination of MBT Spark using ORION optimization
  – Offset spark added to MBT

• Repeatability points are added
  – Center point of factor ranges
  – Used to check verify model quality
Data Gathering in the Test Cell with ORION

Part 1: Parallel Control of Spark CA50, Set stepwise VVT

- Store the initial values for the spark advance for reset at the end of the step.
- Start the parallel control for spark advance.
- Set the speed/load setpoint from the experiment design.
- Store the VVT value for reset.
- Store flags from the experiment design.
- Turn on VVT permission and set the VVT stepwise.
- Stabilize the temperature
- Change the dyno mode to speed / alpha to lock the air path.
Part 2: Set Stepwise Lambda

- Store the initial values for the Lambda for reset at the end of the step.
- Set the Lambda permission and set Lambda stepwise.
- Stop the parallel control for spark advance.
Part 3: Optimization

- Find optimal torque by sweeping spark. Exhaust temperature and knock are monitored to define boundaries.
- Alternatively, if this is a repeatability point, then set to the desired spark in the test plan. After every 10 experiment design points a repeatability point is run using the center point for each region to determine the variation of the response values.
- Stabilize for 10 seconds and then measure.
- Reset the values if this is a repeatability point.
- Otherwise continue to measure offset spark.
Part 4: Measure Offset Spark, Reset Starting Values

- Increment the spark advance by the offset spark value from the experiment design.
- Stabilize and measure.
- Reset the initial values and proceed to the next step.
Data Review

• The data is imported into EasyDoE Toolsuite and reviewed via a user interface
Data Review

• Temperature limits during data gathering set to 750°C
  – This was conservative; difficultly reaching lambda = 1
• Aftermarket Lambda sensor used for AFR feedback control
  – AFR calculated from bench was more reliable
  – Resulted in variation in the repeatability measurements for emissions

Lambda < 1 as speed / load increases
• The data is associated with the factor definition and modeled
• A best model is selected for each response and stored as a result model
EasyDoE Fitting Methods

- Model fitting is done automatically in EasyDoE Toolsuite
- The following polynomial fitting methods are run for each model

<table>
<thead>
<tr>
<th>Polynomial Fitting Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Standard Regression</td>
<td>Least Squares Estimation</td>
</tr>
<tr>
<td>2. Minimize PRESS</td>
<td>The PRESS value is used to select the model terms.</td>
</tr>
<tr>
<td>3. Stepwise Fit</td>
<td>Stepwise regression for term selection</td>
</tr>
<tr>
<td>4. OLS</td>
<td>Orthogonal Least Squares Estimation</td>
</tr>
<tr>
<td>5. T-test</td>
<td>Tests each coefficient to be zero with a specific probability (model structure). If the coefficient is likely to be zero it is taken out.</td>
</tr>
<tr>
<td>6. Robust Regression</td>
<td>Detects the bad data points and build models without these points.</td>
</tr>
<tr>
<td>7. Robust Regression + Minimize PRESS</td>
<td>Model is built without bad data points and trained with the 'best' terms selected by 'Minimize PRESS' algorithm.</td>
</tr>
<tr>
<td>8. Robust Regression + Stepwise Fit</td>
<td>Model is built without bad data points and trained with the 'best' terms selected by 'Stepwise Fit' algorithm.</td>
</tr>
<tr>
<td>9. Stagewise Regression</td>
<td>Incremental Forward Stagewise Algorithm i.e. incremental coefficient adaptation in direction of highest correlation to the current residuals.</td>
</tr>
</tbody>
</table>
Model Quality Analysis

Repeatability (%) = \( \text{Average} \left( \frac{\sigma}{\text{mean}} \right) \)

\* of the repeatability points

Model Quality (%) = \( \frac{RMSE}{\text{Range}} \)

Repeatability < Model Quality_{\text{Fit}} < Model Quality_{\text{Valid & Ver}} < 5\%

- Repeatability and Model Quality should correlate
- The variability of the AFR sensor resulted in higher repeatability values for emissions
Optimization Requirements

• In Model Evaluation a grid of speed / load points is defined:
  – Speed 3000 to 5000 in 200 RPM increments
  – Relative Load 50 to 100% in 10% increments

• A weighted sum gradient descent method is selected.
  – +1 Maximize the response
  – -1 Minimize the response
  – 0 No optimization on the response

• Three optimizations:
  – Minimize BSFC: BSFC weight is set to -1
  – Minimize BSFC: BSFC weight is set to -0.5.
    • Min HC/CO/NOx HC/CO/NOx weights set to -0.05/-0.05/-0.4
  – Maximum torque: Torque weight is set to +1

• A constraint is set to restrict the factor of
  – Spark advance < MBT spark
Model Evaluation – Map Creation

• Maps for each optimization are created in the map editor
  – VVT, Spark, Lambda
• The optimization is performed in Model Evaluation
Model Evaluation – Map Editor

- After the optimization the maps can be edited graphically or in the table.
Model Evaluation

Objective BSFC

Torque

Lambda

NOx

Spark

BSFC

VVT
Conclusion

- **EasyDoE Toolsuite and ORION** provide effective methods for implementing DoE methods
  - Their GUIs make DoE easy to use
  - The results match the physical expectations
Thank you

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