Controller Calibration using a Global Dynamic Engine Model

Marie-Sophie Vogels
Johannes Birnstingl
Timo Combé
CONTENT

- Introduction
- Description of Global Dynamic Model Concept
- Controller Calibration
- Practical Example
- Result Comparison
- Summary and Conclusion
INTRODUCTION

- Challenge “ECU Calibration”
  - Demands of Legislation and Customer
  - Contradicting Targets
  - Diversity of Variants
  - Cost and Time Pressure in Projects

→ XiL-based Calibration Process

XiL = MiL, SiL, HiL
MODEL CONCEPT

- Two stage empirical modeling
  - Global static mean-value model for combustion process
  - Dynamic behavior for the air path
- Usage of artificial neural networks
  - Physically interpretable approach due to thermodynamically based cause-and-effect chain
  - Process outputs models (e.g. for emissions) can be parameterized by steady-state measurements
MODEL CONCEPT

- Global dynamic modeling by partitioning over speed and load
- Using smaller operating areas allow
  - Stimulation of relevant signal frequencies with sufficient distribution of amplitude levels by using APRBS test design
  - Excluding specific combinations of inputs locally
- Separate identification with one dynamic INN allowing different dynamic behavior
- Superposition of semi-global models via validity functions over speed and load

*APRBS: Amplitude-modulated Pseudo Random Binary Signal*  
*INN: Intelligent Neural Networks*
CONTROLLER CALIBRATION

1. Base calibration of the controller in each linear operating point of the engine using standard tuning methodologies

2. Enhanced adaptation of the initial calibration to meet the non-linear plant characteristics and to optimize the control-quality during dynamic driving

**Conventional Approach**

1. Engine → Apply tuning method → Check closed loop performance
2. Controller calibration

**Model-based Approach**

1. Engine → Dynamic and static variations → Global dynamic engine model → Apply tuning method → Check closed loop performance
2. Controller calibration
CONTROLLER CALIBRATION

1. Base calibration of the controller in each linear operating point of the engine using standard tuning methodologies
   - Ziegler-Nichols closed loop tuning method
     - well-known and wide-spread approach based on a “quarter wave decay”
     - meant to give PID loops best disturbance rejection performance. This setting typically does not give very good command tracking performance.
     - revised Ziegler-Nichols tuning rules in order to increase control quality and loop stability
CONTROLLER CALIBRATION

1. Base calibration of the controller in each linear operating point of the engine using standard tuning methodologies
   - Ziegler-Nichols closed loop tuning method
   - ACAT
     - AVL internal tool used for the automated offline calibration of control loops inside the ECU ("Automated Controller Application Tool")
     - The basic controller tuning principle is the so-called “Linear Quadratic Regulator” (LQR) optimization, an algorithm operating with the state-space representation of a control-loop
   - Workflow:
     1. Create controller-structure dependent plugin
     2. Record plant step answers (operating point dependent)
     3. Read and prepare measurement data
     4. Approximate plant transfer function
     5. Calculate according controller parameters
     6. Create controller maps out of local controller parameters
CONTROLLER CALIBRATION

1. Base calibration of the controller in each linear operating point of the engine using standard tuning methodologies
   - Ziegler-Nichols closed loop tuning method
   - ACAT
   - AutoPID Tuner
     - a Matlab-based online controller-calibration tool developed by AVL
     - the plant is identified by an excitation at the critical frequency based on the so-called Auto-Relay tuning
PRACTICAL EXAMPLE

- Air path control of a modern Diesel engine was chosen as representative example for model-based controller calibration.
A global dynamic model was created

- Model validity range:
  - Engine speed: 800 – 4150 rpm
  - Load: combustion border – full load
  - Main timing: +/- 4 °CA
  - Wastegate position: +/- 10 % boost pressure

- 22 local operating areas were identified and combined to one global dynamic model
PRACTICAL EXAMPLE

- The validation results show sufficient modeling quality in terms of dynamic behavior

Extraction of an FTP cycle:

- Effort estimation for generating global dynamic model
  - gross test bed usage: 11 days
  - gross office usage: 10 days
RESULT COMPARISON

- Comparison of stability border between real engine and simulation model

- sufficient reproducibility of gain margin
- no correlation of critical frequency
- but in general the absolute range of the results is well represented
RESULT COMPARISON

- For the comparison of calibration results, a cost function representing the most important criteria from the point of view of an engineer was chosen:

\[ J = \int_{0}^{t_{\text{final}}} (|e(t)|) dt + 10 \cdot \text{mean}(e_{\text{max}}) + 0.5 \cdot \text{mean}(T_a) + 0.5 \cdot \text{mean}(T_s) \]

- Symbols:
  - $J$: Performance index
  - $e$: Control deviation
  - $e_{\text{max}}$: Relative overshoot
  - $T_a$: Rise time
  - $T_s$: Settling time
### RESULT COMPARISON

#### Driving situation

<table>
<thead>
<tr>
<th>Operating point</th>
<th>ACAT</th>
<th>ZN</th>
<th>AutoPID</th>
<th>ACAT</th>
<th>ZN</th>
<th>AutoPID</th>
</tr>
</thead>
<tbody>
<tr>
<td>engine speed (rpm)</td>
<td>injection quantity (mm³/str)</td>
<td></td>
<td>real engine</td>
<td>with conventional cal.</td>
<td>real engine with model-based cal.</td>
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<tr>
<td>1500</td>
<td>25</td>
<td>3.72</td>
<td>4.56</td>
<td>5.75</td>
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<td>2200</td>
<td>35</td>
<td>6.69</td>
<td>4.54</td>
<td>6.35</td>
<td>4.69</td>
<td>6.93</td>
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<td>2800</td>
<td>50</td>
<td>7.15</td>
<td>12.21</td>
<td>7.59</td>
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<td>14.10</td>
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<tr>
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<td>7.38</td>
<td>13.42</td>
<td>8.08</td>
<td>6.41</td>
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#### Setpoint steps (+/- 10%)

<table>
<thead>
<tr>
<th>Pedal steps</th>
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2nd CDL Workshop – Model Based Calibration Methods: Controller calibration using a Global Dynamic Engine Model
RESULT COMPARISON

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<td></td>
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Comparison of resulting control quality - ACAT

Comparison of resulting control quality - Ziegler-Nichols
RESULT COMPARISON

Controller calibration using ACAT approach on real engine
Controller calibration using ACAT approach on global dynamic model
SUMMARY and CONCLUSION

- Model concept in general suitable for controller calibration
- But: model quality not sufficient at critical point of the plant, even though the absolute range of the critical characteristics was identical
- Three different controller calibration methods were investigated
- Algorithm based on the time domain (→ ACAT) shows in general better robustness compared to algorithms based on the critical point (→ Ziegler-Nichols / AutoPID)
- The calibration using the simulation model leads in principle for all methods to stable controller behavior whereas ACAT show less deviation in quality
- Due to the generation effort of the model, it is only recommendable in combination with other calibration tasks
- But: the usage of such a model enables a more complex optimization algorithm based on the non-linear and operating range dependent behavior of the engine like it is described in modern ECU functionalities (e.g. transient correction parameters, different parameters for large and small deviation window) → next step of development
Controller Calibration using a Global Dynamic Engine Model

THANK YOU VERY MUCH FOR YOUR ATTENTION