DESIGN OF ONRAMP MODEL PREDICTIVE CONTROL FOR ON-ENGINE AND GT-POWER TRANSIENT VALIDATION

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Abstract
For Honeywell it is essential to match and validate turbocharger components within complete engine environments involving appropriate control systems. This paper describes the methodology of design, integration and validation of OnRAMP model predictive control strategy for on-engine and GT-Power model applications. Furthermore, a demonstration on an example of Honeywell 2.0L engine equipped with a twin-scroll turbocharger in both measured and co-simulated driving cycle is included.

1. INTRODUCTION

The tighter legislation limits on fuel consumption and emissions adopted around the world have led to increasingly complex internal combustion engine architectures. This drives more and more advanced control strategies in line with comprehensive testing procedures to be implemented in order to confirm the real benefits of new technologies. Furthermore the turbochargers are becoming essential performance component on wide variety of applications.

This makes matching and validation of turbocharger components within the complete engine environments an essential part of the development process. It is however important to consider broad variety of both steady and transient engine operating conditions during the validation. Special attention needs to be paid especially to the vehicle certification procedures based on driving cycle tests.

The common bottleneck for performing these on-engine and simulation-based transient assessments is the design and deployment of appropriate control strategies suitable for increasing engine complexity. This paper demonstrates how this challenge may be addressed via Model Predictive Control (MPC) and Honeywell OnRAMP Design Suite process and tooling, which together can significantly reduce the time required for control deployment on a given application.

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This article also demonstrates Honeywell OnRAMP Design Suite capabilities on examples of both real hardware testing and GT-Power Model in the Loop (MIL) simulations.

2. TARGET ENGINE APPLICATION

For purpose of practical demonstration of OnRAMP capabilities a Honeywell 2.0L gasoline engine equipped with a twin-scroll turbocharger has been selected. The engine features contemporary engine technologies like gasoline direct injection, variable intake cam timing, two switchable exhaust cam profiles or intake tumble flaps.

Figure 1: Engine Layout and Performance

3. MPC DESIGN USING ONRAMP DESIGN SUITE

MPC has been the preferred control methodology in process industries for a long time thanks to its rapid, systematic approach. In recent years the adoption in the automotive controls community has increased rapidly due to advances in theory allowing processing time reduction, as well as due to increasing computing power of the Engine Control Units (ECUs) themselves.

Honeywell OnRAMP Design Suite offers seamless workflow from start to finish allowing to reduce development time needed to practically adopt MPC technology in an industrial environment. This approach is then scalable to a variety of applications and control problems.

The figure below outlines the key steps in an MPC development.

Figure 2: OnRAMP High Level Workflow

It is important to stress that all these steps are supported by Honeywell OnRAMP Design Suite tooling allowing accelerated controller design process and easy on-engine deployment.
3.1. Modeling

OnRAMP is a model-based control design process that delivers and uses medium-fidelity models based on first principles physics, combined with semi-empirical functions. The model itself is an intermediate product of a larger OnRAMP model predictive control design process and runs in Simulink, while the OnRAMP component library supports a variety of engine layouts.

The model belongs to the category of so-called grey box models. The structure of such a model is based on physics, but its parameters (most of which still have physical meaning) are optimized automatically by Honeywell OnRAMP Design Suite tooling to achieve good fitting to the engine measurements. Such an approach offers a balance between complexity and accuracy. Grey box models deliver physical soundness, simplicity, low number of parameters and yet still sufficient accuracy for control purposes.

3.2. Control Design

The MPC control design itself consists of setpoint, feedforward and feedback parts.

3.2.1. Control Problem Definition

The control problem definition is a crucial step, in which the user makes decisions on how the controller will utilize and manipulate system inputs and outputs. Selection of correct control strategy is a base stone required to achieve higher level objectives. However, for on-engine validation a pragmatic choice must be made depending on the available hardware and measurement possibilities.

The controller configurations for the Honeywell 2.0L engine are shown in the following table.

<table>
<thead>
<tr>
<th>Turbocharger</th>
<th>Control Strategy</th>
<th>Actuators</th>
<th>GT-Power</th>
<th>Test Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>GT2256</td>
<td>Pressure</td>
<td>WG, Throttle</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>GT2256</td>
<td>Torque</td>
<td>WG, Throttle</td>
<td>✔️</td>
<td>✔️</td>
</tr>
</tbody>
</table>
The pressure and torque targeting control problem definitions were considered. In both cases an electronic throttle valve (TVA) and a pneumatic waste gate (WG) actuator were operated by OnRAMP. While the pressure control strategy uses intake manifold and boost pressure signals available to the ECU, the torque targeting strategy enables the real-time control of the online measured and corrected test cell torque.

3.2.2. Feedforward Design

The setpoint and feedforward part utilizes OnRAMP engine model and optimization to find the optimal steady state values of actuator signals, such that the required setpoint is reached and all design constraints and requirements are satisfied. Consequently the feedforward actuator positions are found for each operating point.

![Figure 4: Example of Setpoint and Weighting Tables](image)

The core of the feedforward design process is a nonlinear constrained least squares optimization algorithm that minimizes the objective function of weighted control targets. Honeywell OnRAMP Design Suite allows user to adjust the priorities for this optimization as well as to visualize the results in friendly desktop environment.

Furthermore, as OnRAMP implements linear MPC the non-linear model is linearized at feed-forward positions and these linear models are further automatically processed and verified. This is one of the key steps for successful design of MPC feedback control in the next step.

3.2.3. Feedback Design

While the feedforward allows an immediate open-loop reaction on a change of engine operating conditions (e.g. engine speed, load) the feedback ensures robustness by eliminating the control error arising from model inaccuracies and variability of environmental conditions. The MPC cost function then consists of a combination of penalties for actuator movement, tracking error and soft constraints.
The feedback control action needs to be tuned correctly in order to achieve the desired performance. This is typically done by applying corrected MPC cost function weighting, as well as by the correct choice of other MPC parameters, such as prediction horizon or blocking.

Honeywell OnRAMP Design Suite facilitates the MPC feedback tuning using an automatic algorithm in order to achieve similar user defined requirements on robustness and bandwidth across the complete operating range of the engine. This feature actually allows common design for wide variety of engines and plants. The controller tuning then consist mainly of the adjustment of relative weights of controlled and manipulated variables and of the choice of prediction horizon blocking. This leads together with earlier model checks to systematic and intuitive design and tuning of an MPC feedback control.

3.3. Deployment

Finally the Honeywell OnRAMP Design Suite generates the C code, which is ready for ECU integration and on-engine testing, as well as for further validation within MIL environments involving high fidelity engine models, such as those created using GT-Power software.

4. GT-POWER CO-SIMULATION VALIDATION

As the access to the engine test cell is limited and many of the hardware parts are unavailable in the various stages of their design process, the ability to validate also within the model in the loop (MIL) environments becomes essential. The use of well-established industry practice of high fidelity GT-Power models is a logical choice for such simulations.

4.1. Methodology

OnRAMP MPC is a suitable controller for this purely software level utilization with thermodynamic engine simulations within GT-Power software (a part of the GT-Suite package). The advantages of such an approach are the flexible and easy-to-adjust control objective definition, as well as reduced time for control software deployment. In this application, the co-simulation between the OnRAMP MPC operating the TVA and WG actuators in a GT-Power engine model played an important role in the early validation of the controller. Furthermore, this kind of MIL simulation is used for preliminary tuning of the OnRAMP controller as a preparation for its first on-engine validation. Although the accuracy of such pre-tuning strongly depends on the level of
fidelity of the thermodynamic engine model, the described approach generally helps even further accelerate the engine control design process.

4.2. Co-simulation Prerequisites

The basis of model in the loop simulations is the thermodynamic engine model. Once available it can either be used for the OnRAMP controller identification, or an existing controller designed using real engine data may be used. The next step is to prepare the co-simulation environment in Simulink, where the deployed OnRAMP S-function needs to be supplied with appropriate signals routing through the communication block (so called GT-link) to the engine model and back.

![Co-simulation Workflow Diagram](image)

**Figure 6: High Level MIL Co-simulation Workflow**

In general there are several options for the management of the co-simulation between Simulink & GT-Power depending on the choice of co-simulation master and coupling technology. The first option is to import the Simulink model into GT-Power as a dynamic linked library and perform the co-simulation within GT-Power using its solver. In the second option GT-Power solver is called by the Simulink master and both solvers run in parallel. The last option is to export the GT-Power engine model into a standalone Simulink S-Function MEX file and run the co-simulation entirely within Simulink solver.

On the example of Honeywell 2.0L engine, the second option was selected allowing for the highest flexibility in the simulation time step length management and model changes implementation. In order to facilitate the control performance assessment the recorded test cell signals (both instantaneous control targets and feedbacks) are used as the co-simulation inputs, so that the outputs are inherently synchronized with the measured data. Thanks to that the same targets are used throughout the calculation making the subsequent direct comparison of simulation and measurement possible (see the Figures 9 and 10 in the following section).

5. ON-ENGINE VALIDATION
Enabling engine dyno driving cycle (e.g. NEDC) testing and validation is a key driver for the on-engine experiments. Since the driving cycle is defined by a schedule of vehicle speed in the legislation, the engine must be driven in such a way that would allow certain vehicle to follow that requirement. There are generally two main options how to achieve this in an engine test cell environment.

Either a vehicle simulation and a driver controller can be run in parallel to the dynamometer test, so that calculated vehicle speed and engine torque request are available at every moment of the experiment; or the vehicle speed schedule can be transformed into a schedule of a different physical quantity (in our case boost pressure or torque) based on available measured reference or an offline vehicle simulation.

Although the first option offers straightforward design of experiment, the second one was used in this application due to its considerably easier practical realization, while still allowing for engine control quality assessment. Nevertheless, in order to make conclusions on the engine fuel consumption and emissions a subsequent validation of the conformity to the driving cycle specification is required in case of pressure or torque control.

5.1. OnRAMP Integration

In the environment of Honeywell testing laboratory in Brno, the OnRAMP controller runs on an ETAS ES1000 rapid prototyping unit using custom private CAN communication to the ECU, which allows by-passing the standard air path control. In this case the standard control approach uses map based control logic with limited feedback capabilities, using the accelerator pedal position and engine speed as key variables for TVA and WG position control. This also illustrates our motivation to replace it by the OnRAMP MPC controller. The integration of the OnRAMP MPC controller then consists of the following steps.

Sensor readings acquired by the ECU are being forwarded to OnRAMP and consequently generated actuator positions are sent back to overwrite corresponding ECU outputs (TVA and WG positions). At last the test cell CAN network is linked to the
ES1000 unit to bring additional measurements such as torque and turbocharger speed to the OnRAMP MPC.

5.2. Engine Test and Co-simulation Results

The following results show the quasi-NEDC driving cycle validation scenario, where the engine is controlled according to the recordings from a reference vehicle running through a driving cycle test.

5.2.1. Boost Control

Figure 9: Comparison of Co-simulation and On-engine Results in Pressure Control Mode

5.2.2. Torque Control

Figure 10: Comparison of Co-simulation and On-engine Results in Torque Control Mode
6. CONCLUSION

This study was an initial step for using OnRAMP MPC as enabling technology to aid and reduce time required for the assessment of (not only) turbocharger parameters throughout their development process. Both engine and co-simulation with thermodynamic GT-Power engine model driving cycle validations had been performed achieving first promising results. Nevertheless further controller adjustment and refinement is required to gain higher confidence in this hardware selection evaluation methodology.

It can be also concluded that the GT-Power co-simulation represents well the engine thermodynamics and is suitable for development and evaluation of air path control strategies. But special attention shall be paid to the low-level on-engine actuator control mechanisms as this has significant impact on the overall dynamics and performance of the system. Those actuator dynamics are generally not present in GT-Power models causing impression of controller’s higher stability and responsiveness in the co-simulation environment. This paper has however shown that the same OnRAMP MPC controller can be used in both environments.
7. REFERENCES


