

Efficiency Optimization Using a Power-Guided Engine Control for Management of Thermal-and Mechanical Demands Using the Example of a Micro Combined Heat and Power Unit

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ABSTRACT

At a micro-CHP unit the target size of the engine controller is not mechanical torque but thermal and mechanical power. Accordingly, these demands must be implemented by the engine controller. This means that on the one hand a mechanical demand is answered under the boundary condition of the highest actual efficiency and that on the other hand thermal demands have to be processed.

Since the thermal- and mechanical power output is coupled with the actual efficiency, exceeding the nominal load of the thermal power, the actual efficiency can be regulated in order to answer the demand. This can be done in consideration of the maximum achievable actual efficiency. Limits are set by the combustion stability and thermal protection functions.

The functions are modelled with Matlab/Simulink and the ECU code for a rapid control prototyping system is generated.

A dynamic engine test bed for internal combustion engines up to 12 kW was built to verify the motor control functions. The measurement technology for all standard measurements of combustion engines has been selected accordingly to the expected measurement range of small engines.

All measured values together with an interface for test automation are accessible via CAN bus. Because of this the rapid control prototyping controller is able to set any operating point parameters and uses the entire measurement devices from the test bed sensors. The integration of test bed automation in the CAN bus system enables the rapid control prototyping controller to get accesses to electrical quantities such as the actual motor current. This option is also available in CHP units with corresponding control. An efficiency optimization can be shown by adjusting the ignition angle with the active current of the generator as feedback information.

CITATION: Steinmill, J. and Struzyna, R., "Efficiency Optimization Using a Power-Guided Engine Control for Management of Thermal-and Mechanical Demands Using the Example of a Micro Combined Heat and Power Unit," *SAE Int. J. Engines* 8(1):2015, doi:10.4271/2014-32-0080.

INTRODUCTION

The control and regulation of internal combustion engines for use in micro-CHP units has not yet reached state of the technology that is currently in use in automotive industry.

The engines are frequently operated in a stationary operating point without adjustment of the combustion process. Some CHP Units vary the speed of the engine and of the generator to adjust the total system power. Frequency inverters are used to keep constant frequency of the generated electricity.

In automotive sector the torque structure is best available technology. The requested torque by driver derives from the accelerator pedal position and is coordinated with other torque

requests. In the simplest case these requests are converted into a desired air-charge, ignition angle and amount of fuel. The actuators of the engine such as throttle, ignition and injectors are controlled accordingly.

A power guided engine control system being able to answer thermal and mechanical demands enables the decoupling of heat and electrical power generation within the limits of possible efficiencies. Relative heat demands way above average that commonly only have a small part of the load profile of one CHP unit on an annualized basis, can be answered without compromising a possible necessary electricity production.

An adaption of the ignition angle with changing gas composition has to be done in order to fulfill the requirement of high electrical efficiency.

At first the development environment for verifying the new engine control functions is introduced. The used test bed and the engine are described. Next the torque structure is outlined representing the state of technology in mobile applications. The next section discusses the theory of a power-guided engine control and explains the different operating modes with corresponding boundary conditions. Finally, the implemented structure is shown and the development environment for the rapid function prototyping is described in detail. In the second part a study on the use of the active current signal from the frequency inverter is shown to determine the optimal ignition angle.

TEST BED USED FOR EVALUATION

The test bed is built for internal combustion engines up to 12 kW and 35 Nm. The measurement technology for all standard measurements of combustion engines has been selected according to the expected measurement range of small engines. The main approach is designing the measurement and control setup optimized to be used with a rapid control prototyping ECU.

The rapid control prototyping ECU allows fast implementation of control algorithms while simulating and verifying these algorithms offline and on the engine test bed. [1] The common practice consists of the following steps:

1. Model-based function development
2. Offline simulation
3. Automatic code generation
4. Testing and verification
5. Calibration
6. Documentation

All devices from the test bed send their values in real time on CAN bus. These signals can be used as inputs to the rapid control prototyping ECU. The benefits of this approach are:

- Fast and simple access to any value. The network is managed by a CAN database that can be processed by the management software of the ECU.
- No need of redundant sensors. For instance the average value from the low pressure indicating device can be used as input signal for the load calculation.
- For research and testing purposes high accuracy and industry type sensors can be used.
- The standard test-setup at an engine test bed covers a lot of signals that can be used in control development such as exhaust temperatures, volume flow of the cooling circuit.
- The ECU is able to communicate with the test bench

automation system for instance to set the speed of the dynamometer or to set temperatures of the cooling water conditioning system.

- All measurement and calibration values are processed in a single software system
- No additional measurement error by analog digital conversion

The statistical values of each combustion (indicated mean pressure, mass fraction burned points) will be sent to the CAN bus before next ignition of the corresponding cylinder is fired. These values can be used to develop a closed loop control for the 50% mass fraction burnt point. The raw data of the pressure curves are excluded from the bus because the data rate is too high. The complete bus setup is shown in [figure 1](#).

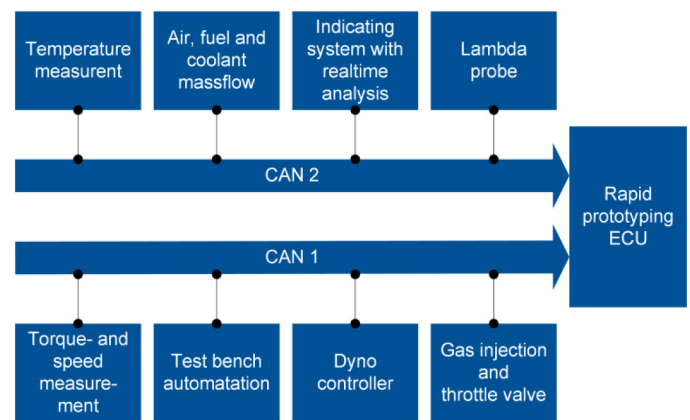


Figure 1. CAN bus design of the small engine test bed

ENGINE USED FOR EVALUATION

The combustion engine is a micro CHP unit engine. The choice of technology is adapted to the requirements of an engine for use in a micro CHP unit. The engine specifications are given in [table one](#).

Table 1. Engine specifications

Type	Four stroke spark ignition engine
Displacement:	272,6 cm ³
Stroke:	73 mm
Bore:	65 mm
Number of cylinders	1
Connecting rod ratio	0,291
Compression ratio	12.5:1 10.9:1 (natural liquid gas)
Rated Speed	3600 rpm
Number of Valves	2
Valve control	OHV
Cooling system	Water cooled
Carburation	External carburation
Air fuel ratio	1

DESIGN OF A POWER-GUIDED ENGINE CONTROL

Torque-Guided Engine Control Systems (State of the Technology)

All torque demands are coordinated by the torque structure (figure 2). In the system part "Torque Demand" all incoming requests (e.g. driver's requested torque, heating functions demands of catalyst, idle speed control, ride comfort functions) are collected and passed to functional part "Torque Structure".

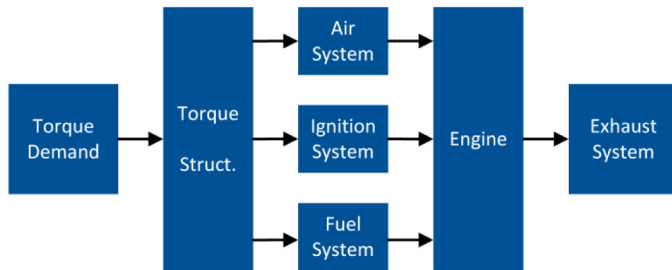


Figure 2. Torque Structure

The system part "Torque Structure" processes the torque requests and sets the values for the air-, fuel- and ignition path to provide the desired torque. Fast torque changes that cannot be answered by the air path must be realized by the ignition and fuel path. The prioritization of the paths is based on the desired dynamic. The air path has priority in case of sufficient dynamic. Torque reductions on the ignition path decrease the efficiency and interventions in the fuel path can affect the emissions negatively.

In order to respond to a dynamic torque demand on the ignition path, the ignition angle efficiency characteristic line is used. It applies to all operating points of the engine and indicates the relative torque change in deviation from the optimal ignition angle. Thus, the desired ignition angle can be calculated by the desired efficiency. Latest possible ignition and therefore the greatest relative reduction in torque is determined primarily by the limit of a stable combustion. In case of a required torque reduction larger than possible by ignition path this will be answered by fuel path. In extreme case the injection of all cylinders is deactivated. [2, 3]

Power-Guided Engine Control Systems

The input variables of a power-guided engine control are mechanical and thermal power demands. In case only one demand is specified it has to be defined under which condition the other has to be answered. If both requirements are known the ratio between mechanical and thermal power, and thus, the actual efficiency is determined. If the actual efficiency for a given total system power cannot be answered in the operating characteristic map with at optimal combustion efficiency then the actual efficiency has to be set.

The efficiency of gasoline engines can be set via the ignition angle. As known from the torque structure the ignition angle efficiency characteristic line applies for each operating point at optimal ignition. This characteristic line is showing the resulting torque reduction as a function of the distance from optimal ignition angle. This characteristic can also be used for power calculations as power is calculated linear by torque and speed.

$$M_e = M_{opt} \cdot \eta_I \quad (1)$$

$$P_e = 2 \cdot \pi \cdot n \cdot M_{opt} \cdot \eta_I \quad (2)$$

Limits of the ignition angle variation are set by combustion stability and thermal stress.

Operating Areas

For an internal combustion engine that operates in a stationary operating point the following energy balance can be established:

$$\dot{Q}_F = \dot{m}_F \cdot H_u = P_e + H_w \quad (3)$$

$$H_w = H_{ex} + \dot{Q}_{co} + \dot{Q}_{ra} \quad (4)$$

The fuel mass flow which is supplied to the engine is combusted with air and converted into mechanical power, exhaust gas enthalpy, the cooling-water heat flow and thermal radiation. Furthermore, it is assumed that the total resulting waste enthalpy H_w will be used for heating. Accordingly H_w is referred to below as thermal power P_{th} .

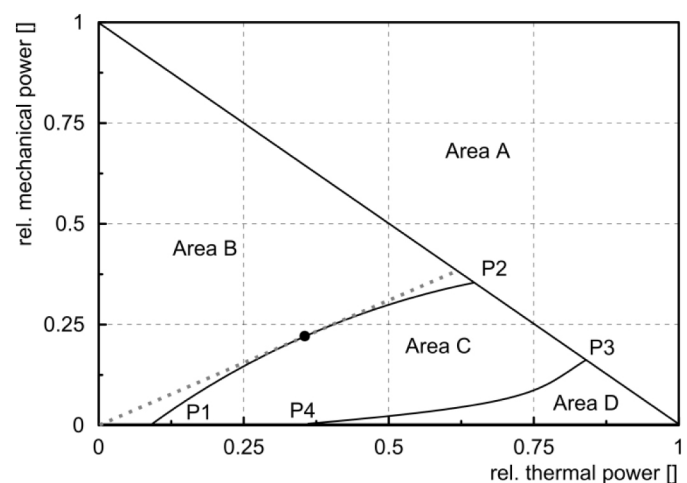


Figure 3. Operating range of a power-guided engine control