Combustion Pressure Controlled SI Engines: New Concepts for Individual Cylinder Control

1. Introduction
2. Experiment Environment
3. Closed-Loop Ignition Timing Control
4. Air-Fuel Ratio Estimation
5. Exhaust gas recirculation control
6. Calculation of cylinder gas components
7. Conclusions

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Institute of Automatic Control
Dept. for Control Systems and Process Automation
Prof. Dr.-Ing. Dr. h.c. Rolf Isermann

History

Control algorithms

- 1976 – Hubbard, Powell (Stanford): Ignition Control
- 1989 – (Honda): Ignition Control
- 1988 – **(Nissan): Ignition Control** (*piezo-electric, spark plug*)
- 1986 – Matekunas (GM): Pressure Ratio
- 1992 – **(Toyota): Lean-Burn Engine** (*piezo-resistive*)
- 1994 – (Opel): Cylinder Pressure Management
- 1998 – (MTU): Peak Pressure Control (Diesel)
- 2000 – AENEAS (Ricardo/ DaimlerChrysler/ Kistler) (*resistive*)

1980 1990 2000

Sensor technology

- 1989 – Texas Instruments: *(piezo-electric)*
- 1996 – BOSCH: *(piezo-resistive)*
- 1998 – Optrand: *(fibre optical)*

Combustion Pressure Sensors for Engine Control

Diesel

- injection timing
- EGR control
- torque control, torque or A/F balancing
- peak pressure supervision

SI

- ignition timing
- A/F ratio, A/F balancing
- EGR/lean limit control
- cold-start and warm-up behaviour

improved functionality

- **emissions**
- **fuel consumption**
- **performance**

- estimation of intake air mass
- camshaft position sensing
- knock detection (SI)

cost equality

- fault detection algorithms
- providing indicated torque signal
- misfire detection

reduced calibration effort

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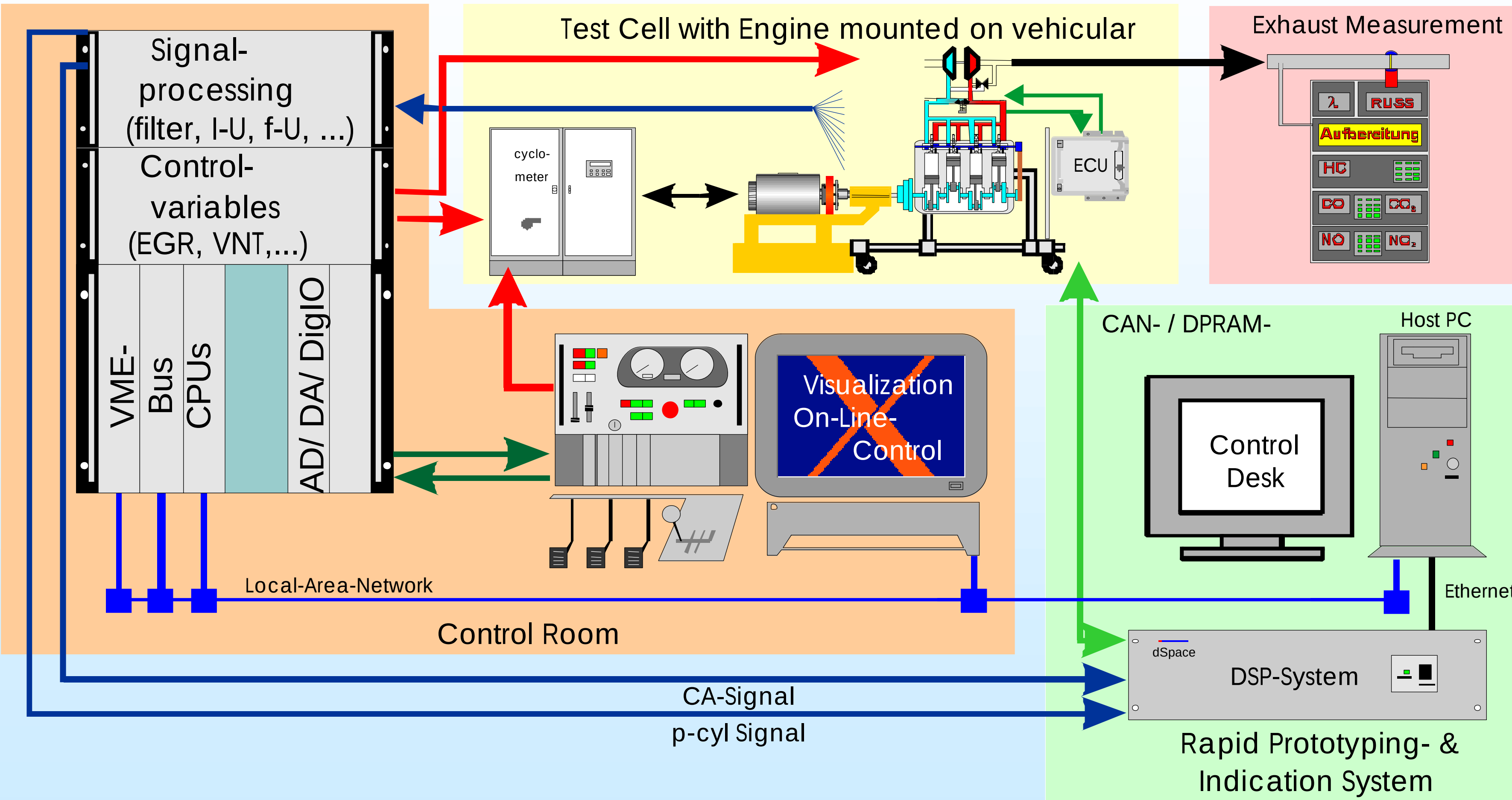
Dynamic Engine Test Stand



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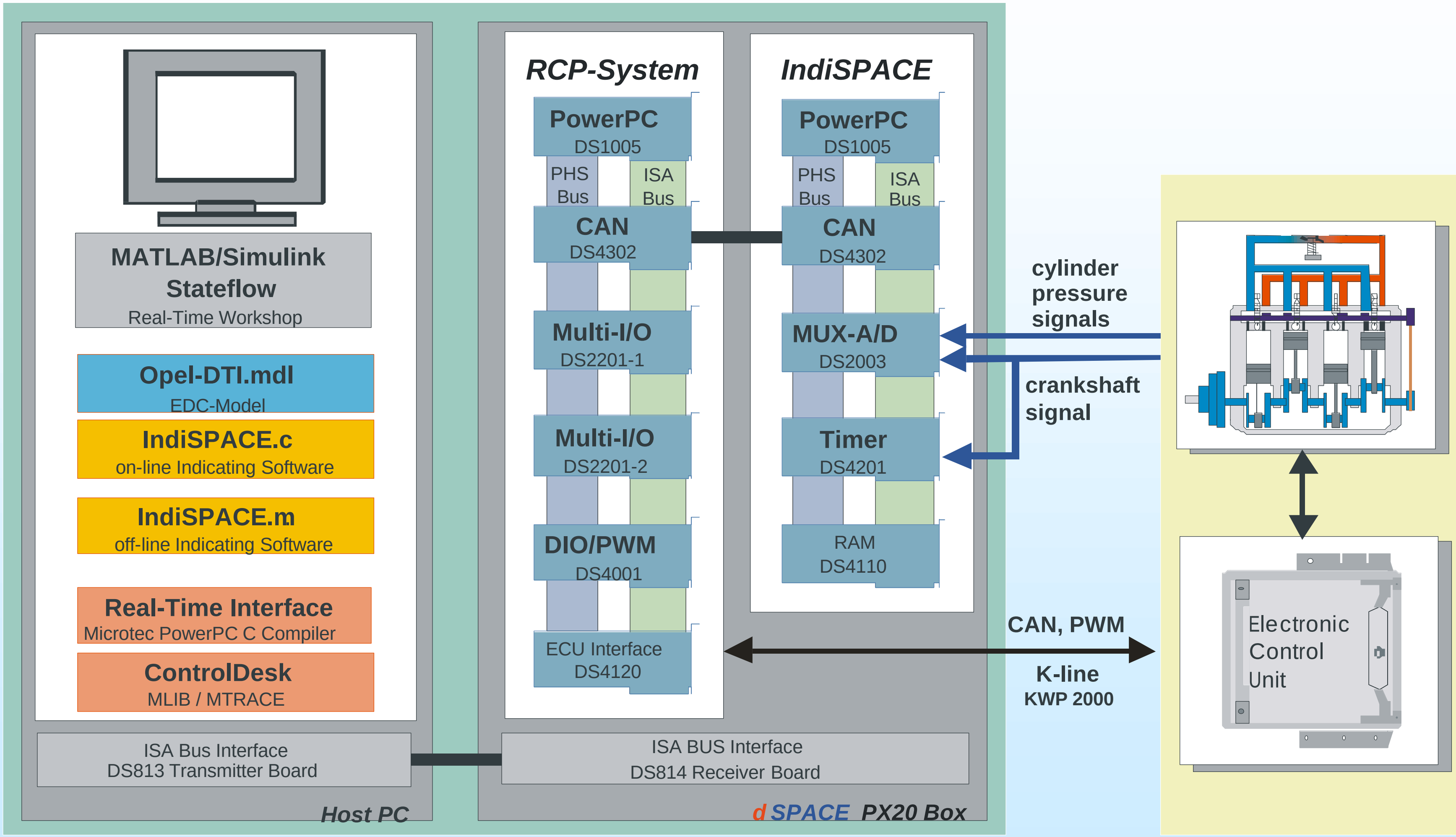
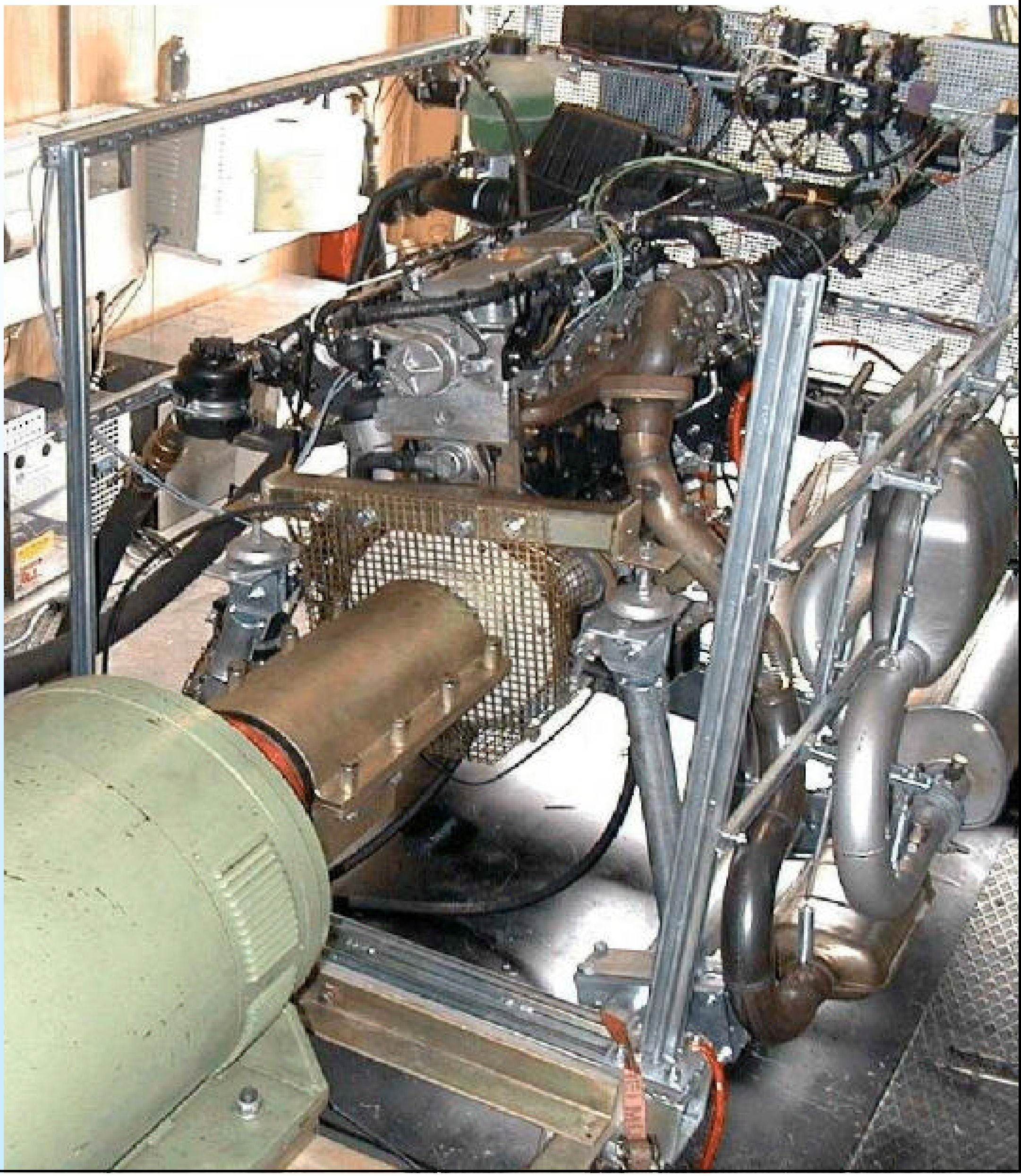
Rapid Control Prototyping and Indicating System



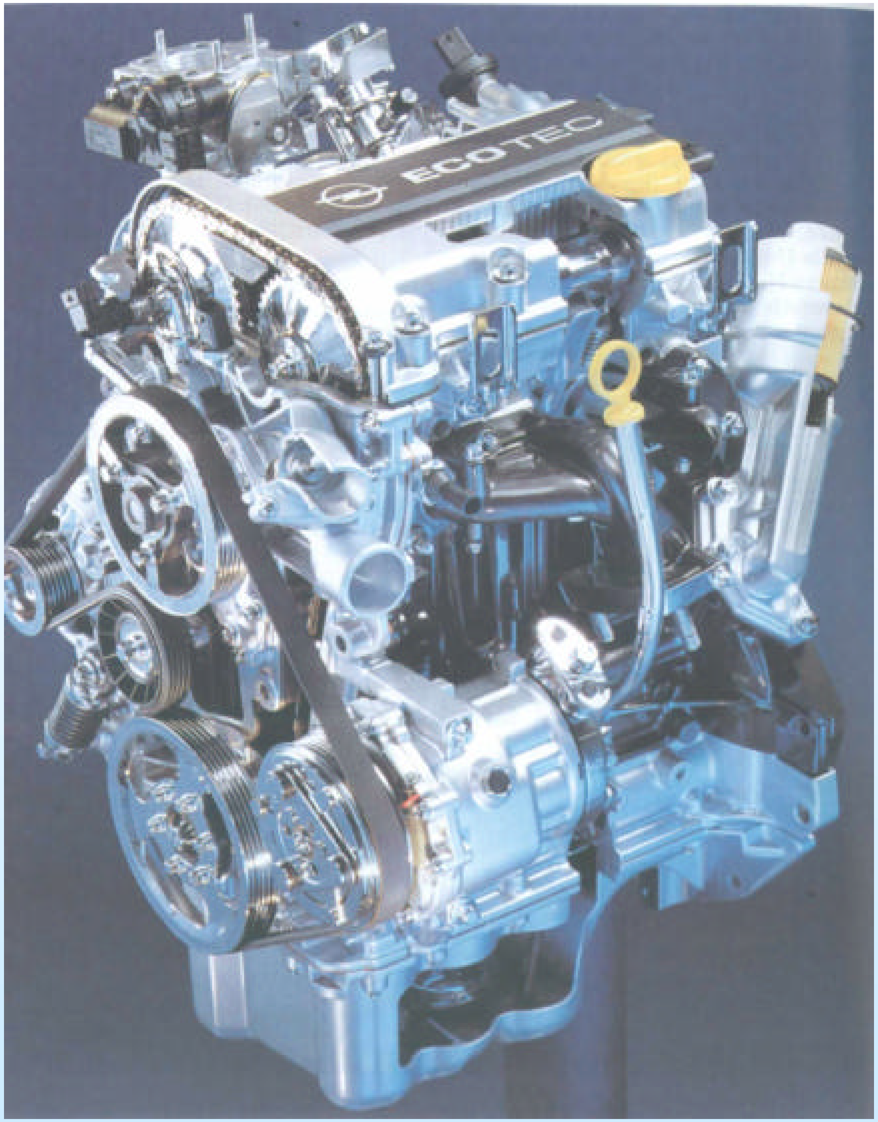
Control Room

IC Engine / Motor



Opel 1.0 Liter,
3 Cylinder SI Engine

- 82 Nm (at 2800 rpm)
- 40 kW (at 5600 rpm)
- electronic throttle control
- exhaust gas recirculation
- cylinder individual ignition timing
- cylinder individual multipoint fuel injection
- fuel mass, ignition and EGR valve can be manipulated externally



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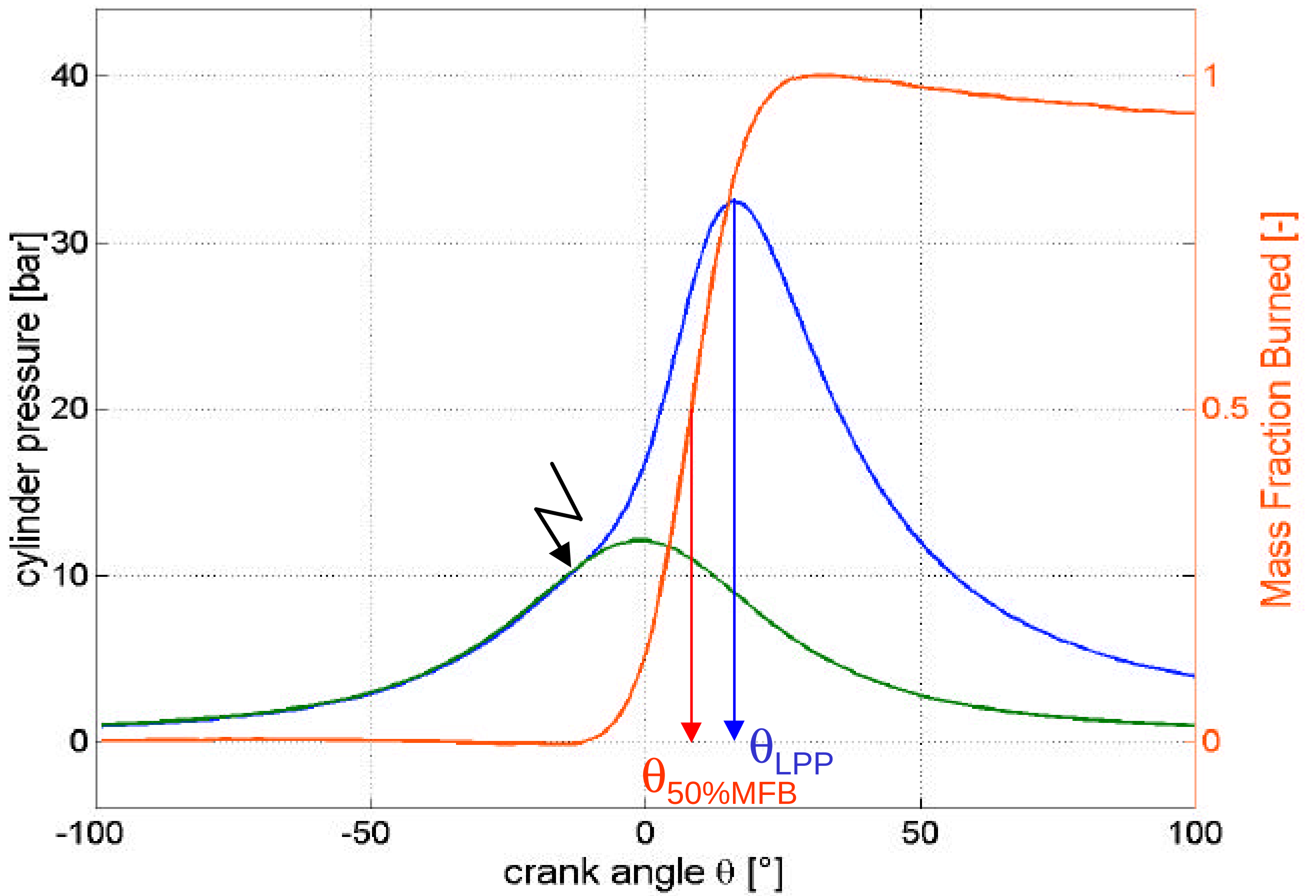
Combustion Pressure Evaluation for Ignition Timing Control



evaluation of
- location of peak pressure
- crank angle of 50% mass fraction burned

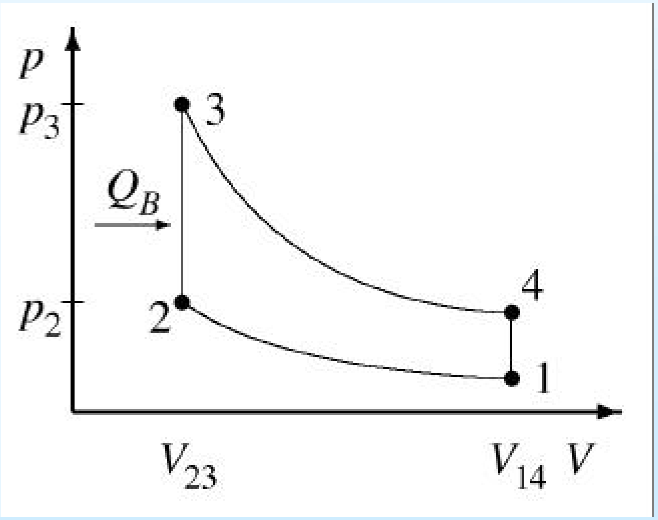
Cylinder Pressure Evaluation

Compression stroke (1→2): $p \cdot V^k = C_1$

Expansion stroke (3 →4): $p \cdot V^k = C_2$

➔ $Q_B \sim C_2 - C_1 = p_{eoc} \cdot V_{eoc}^{\;k} - p_{ign} \cdot V_{ign}^k$

➔ $$x_{MFB}(q) \approx \frac{p(q)V^k(q) - p_{ign}V_{ign}^k}{p_{eoc}V_{eoc}^k - p_{ign}V_{ign}^k}$$



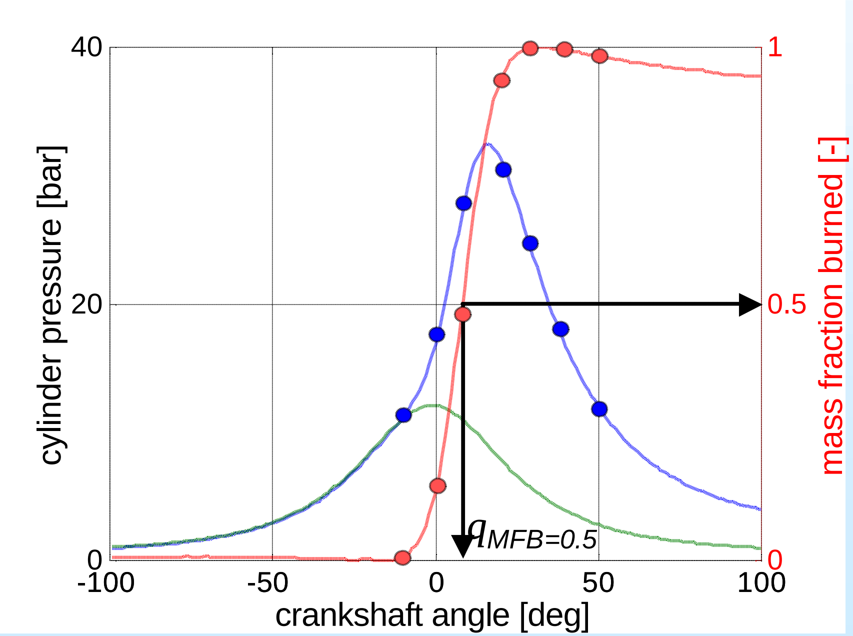
Constant volume diagram of ideal combustion cycle

after end of combustion:

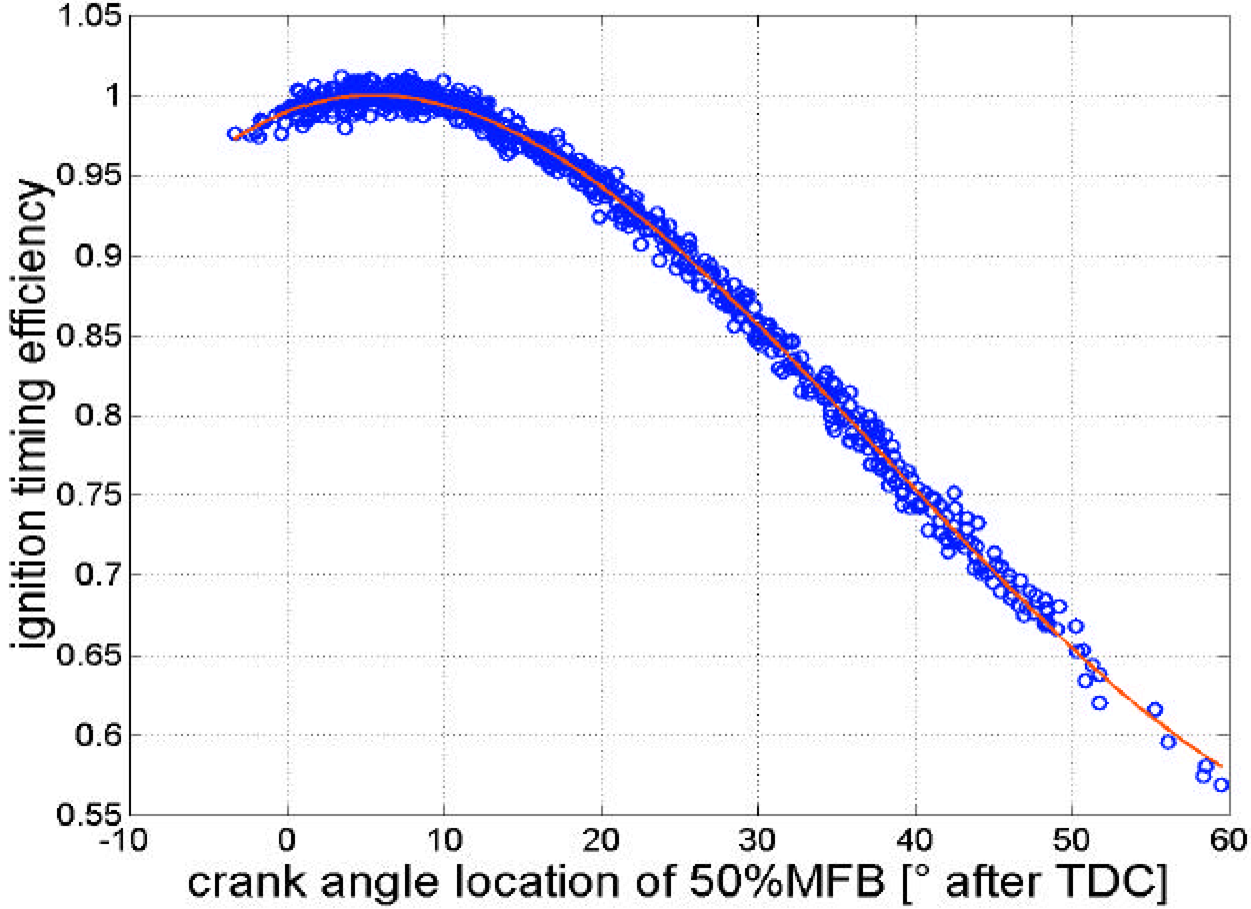
1.) calculate $x_{MFB}(q)$ for $q_{ign} < q < q_{eoc}$

2.) search $x_{MFB}(q) = 0.5$ ➔ $q_{MFB=0.5}$

eoc ... end of combustion
ign ... ignition



Influence of „Location of 50%MFB“ on Indicated Engine Torque



variation of ignition timing at 2000 rpm, 35% load

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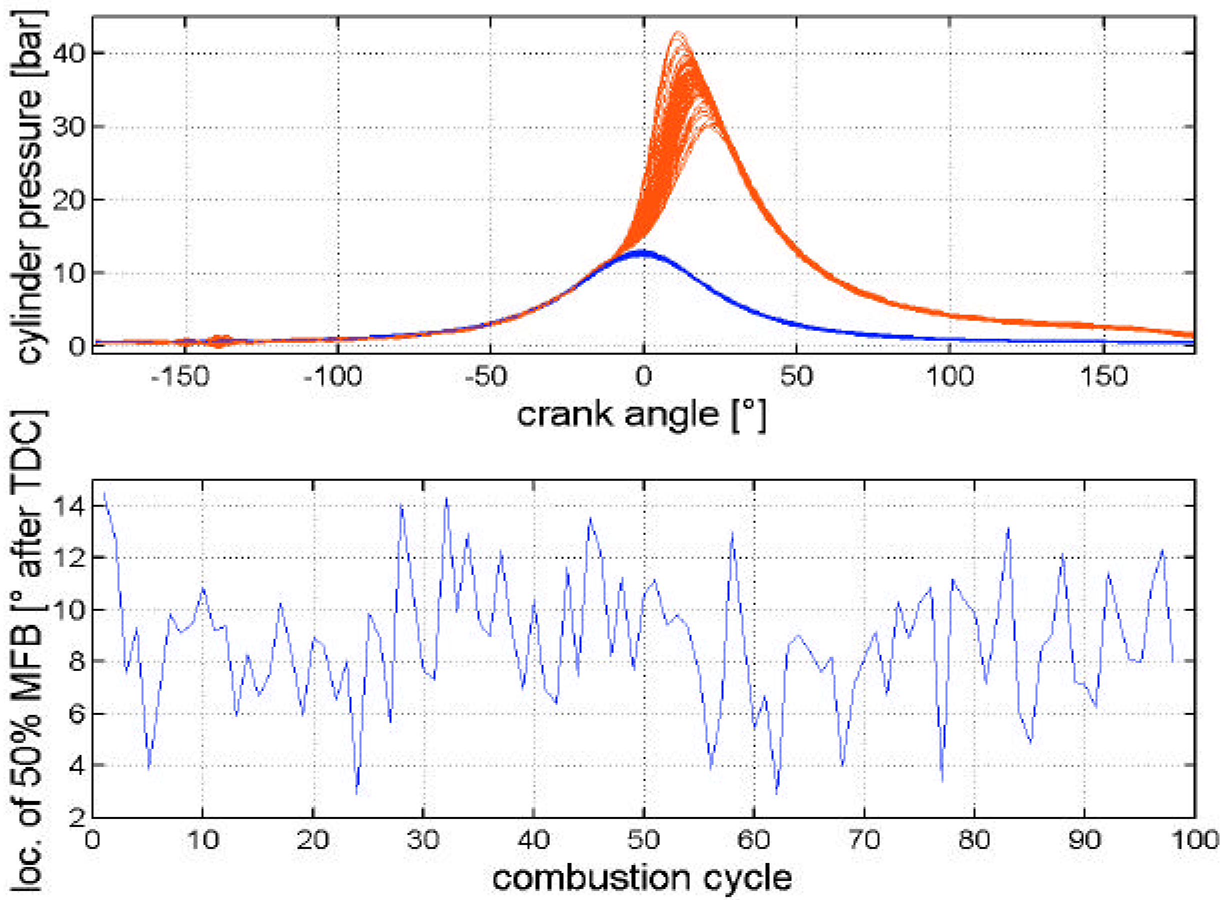
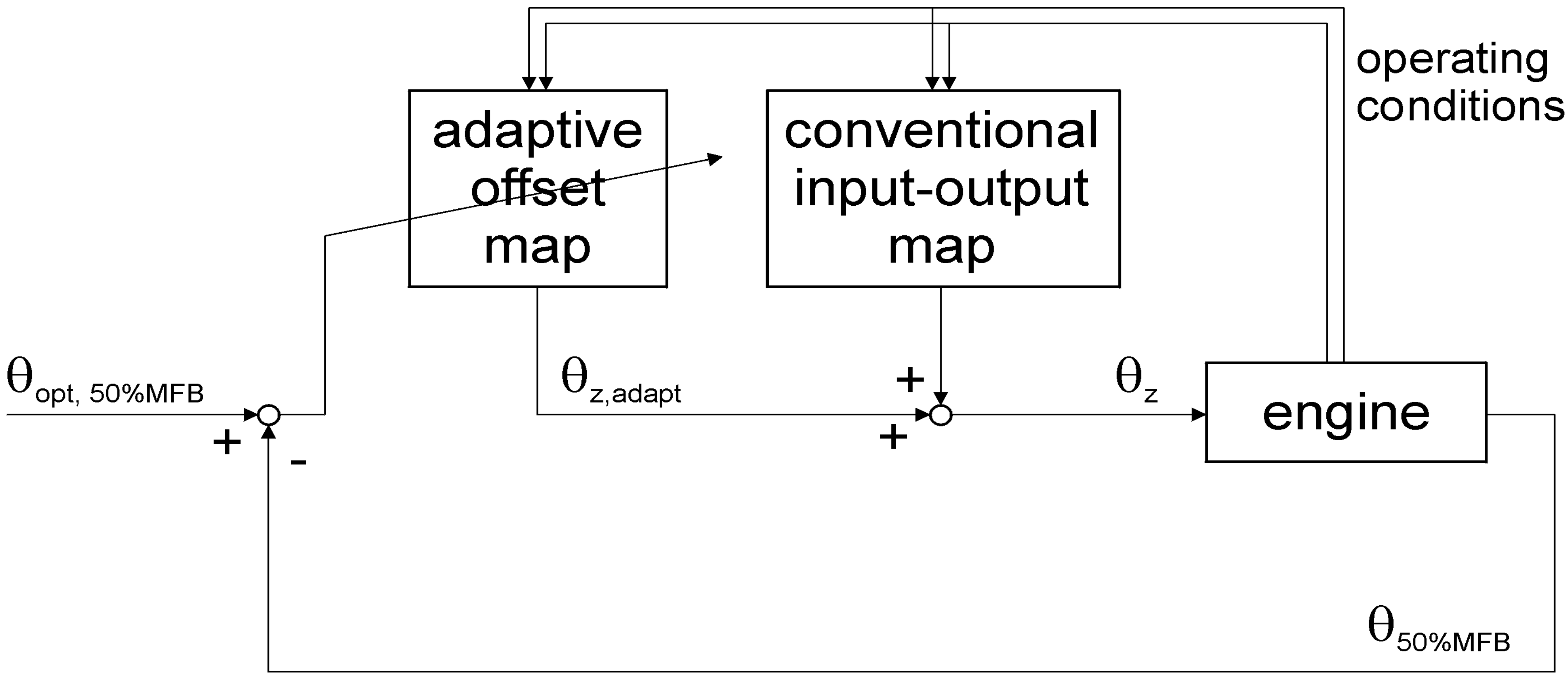
Cyclic Variation of Combustion Pressure Features at Constant Operating Conditions

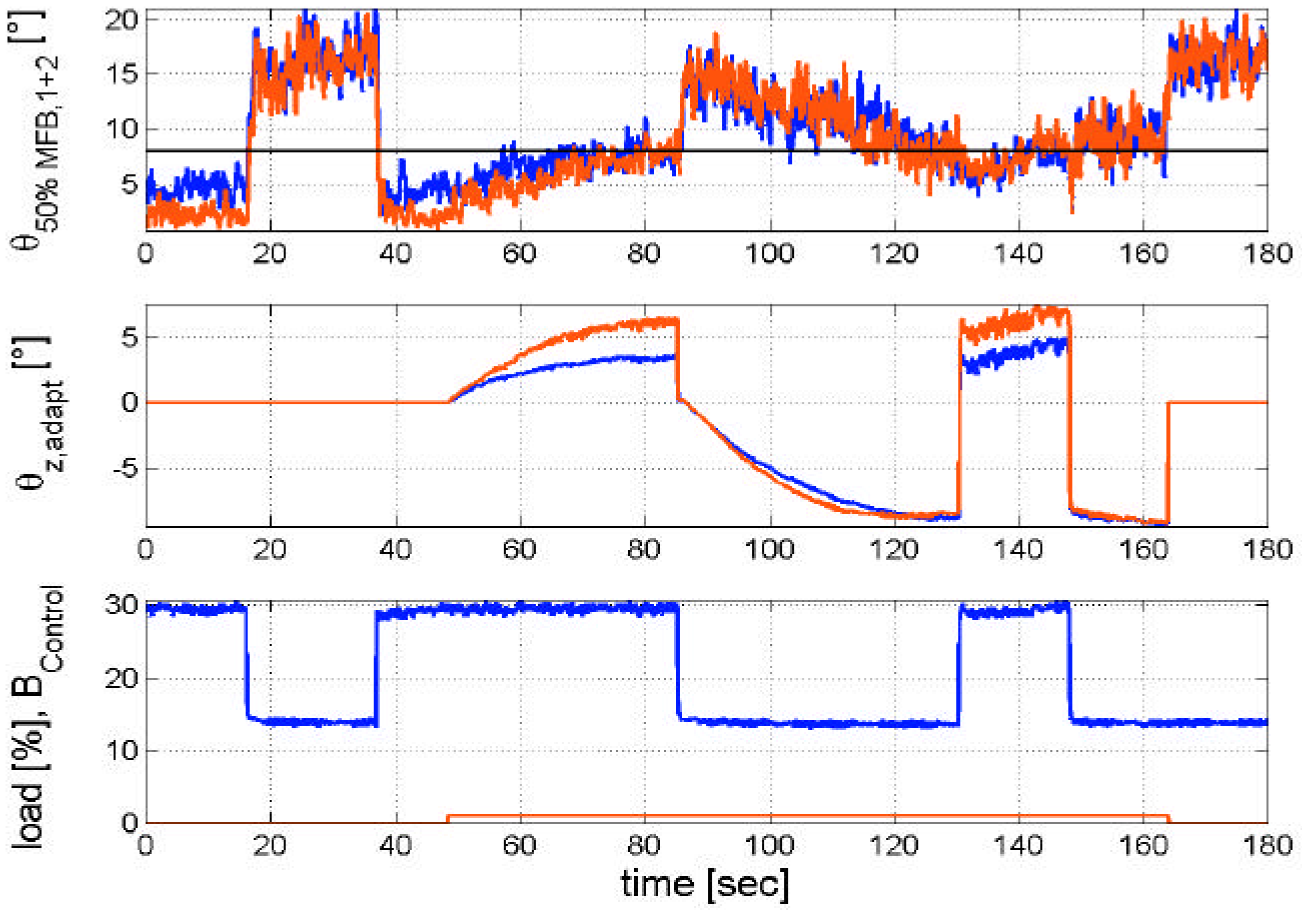


operating condition:
3000 rpm,
50% load,
0% EGR
COV_{Pmi}=1.3%

Structure of Learning Feed-Forward Ignition Timing Control



Learning Feed-Forward Ignition Timing Control during load changes



3000 rpm,
0% EGR,
$\theta_{z,conv} \approx 26°$ b. TDC

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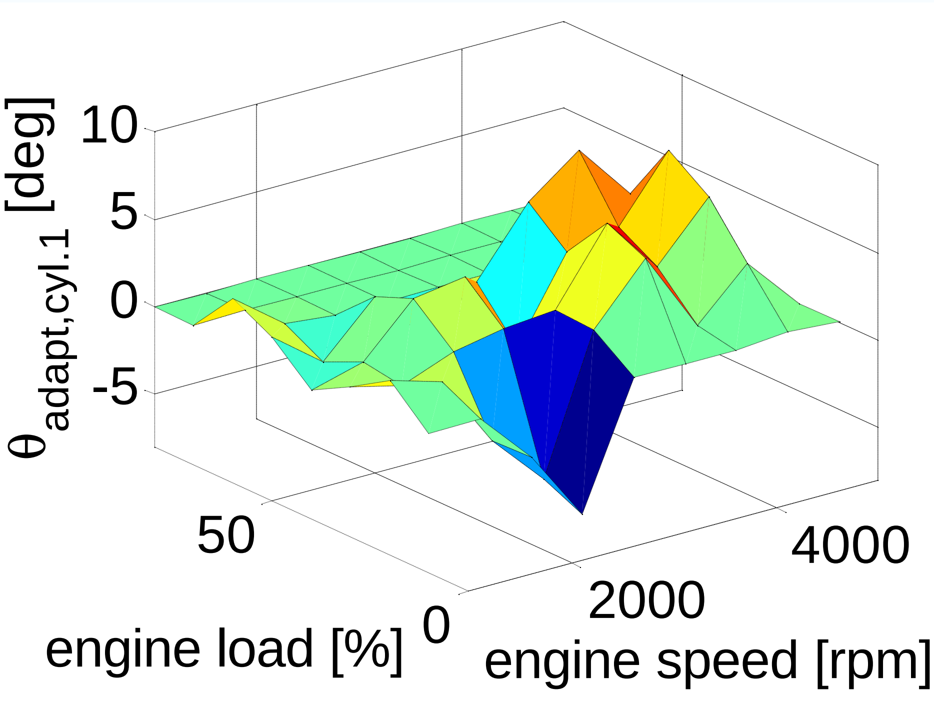
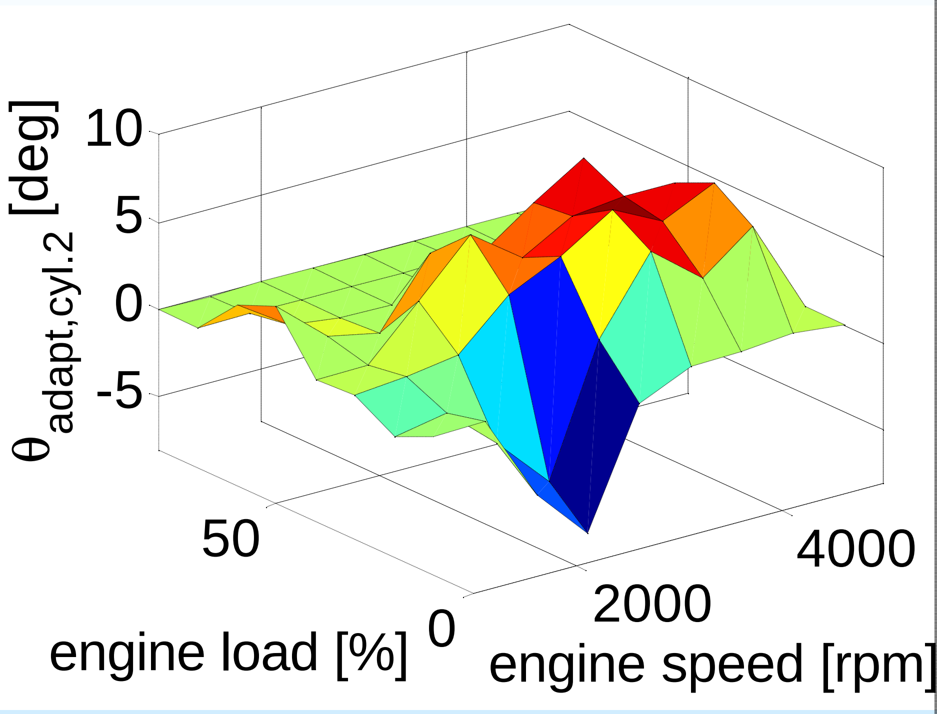
adapted Offset-Mappings



Cylinder 1



Cylinder 2

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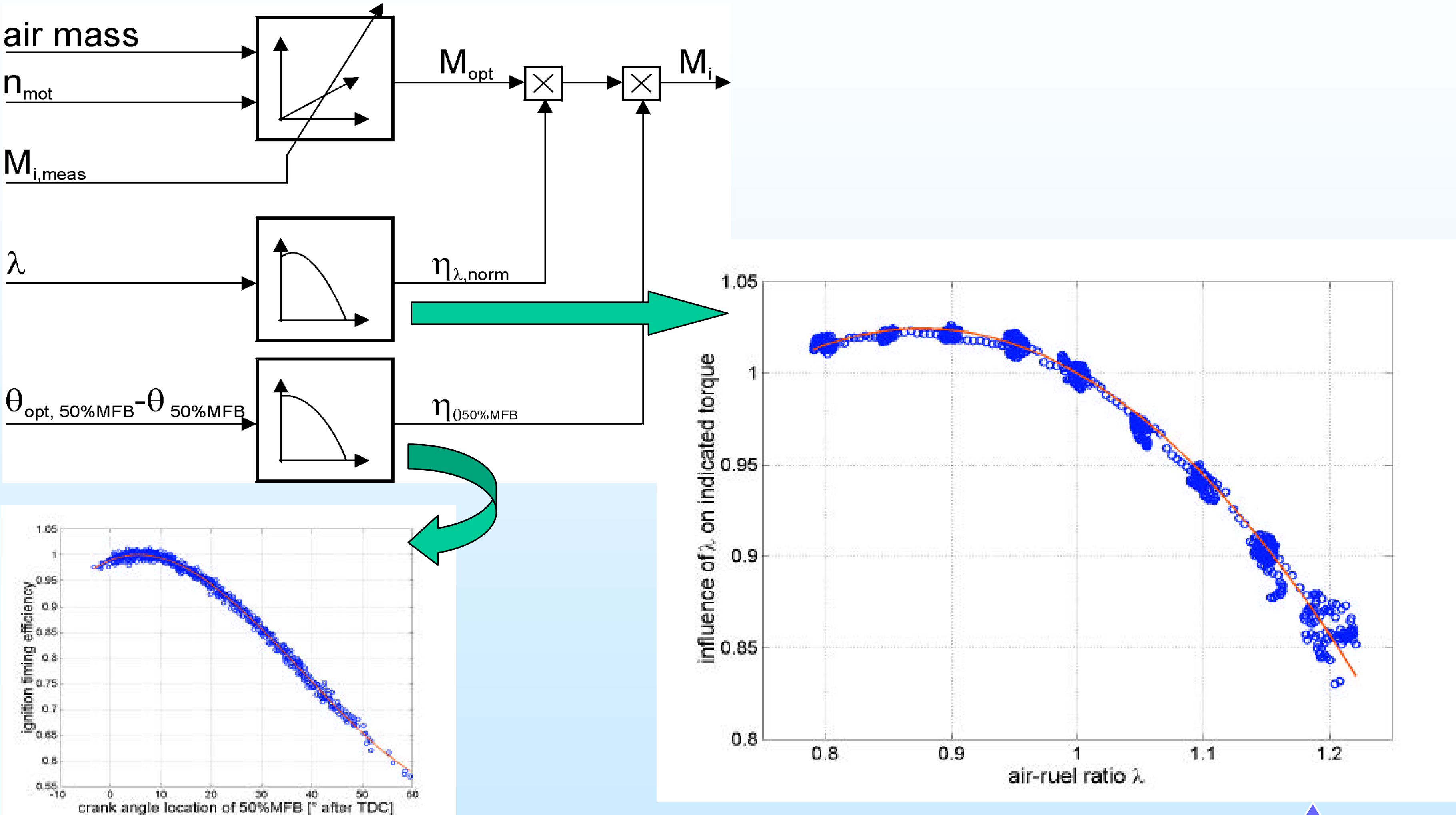
Air-Fuel Ratio Estimation for SI engines

Applications

- estimation of A/F ratio deviation from $\lambda = 1$ when using switching EGO sensors
- estimation of A/F ratio during warm-up (EGO sensor is inactive)
- detection of A/F ratio maldistribution
  - reduced emissions
  - reduced aging of catalytic converter

Indicated Engine Torque Model for A/F Ratio Estimation



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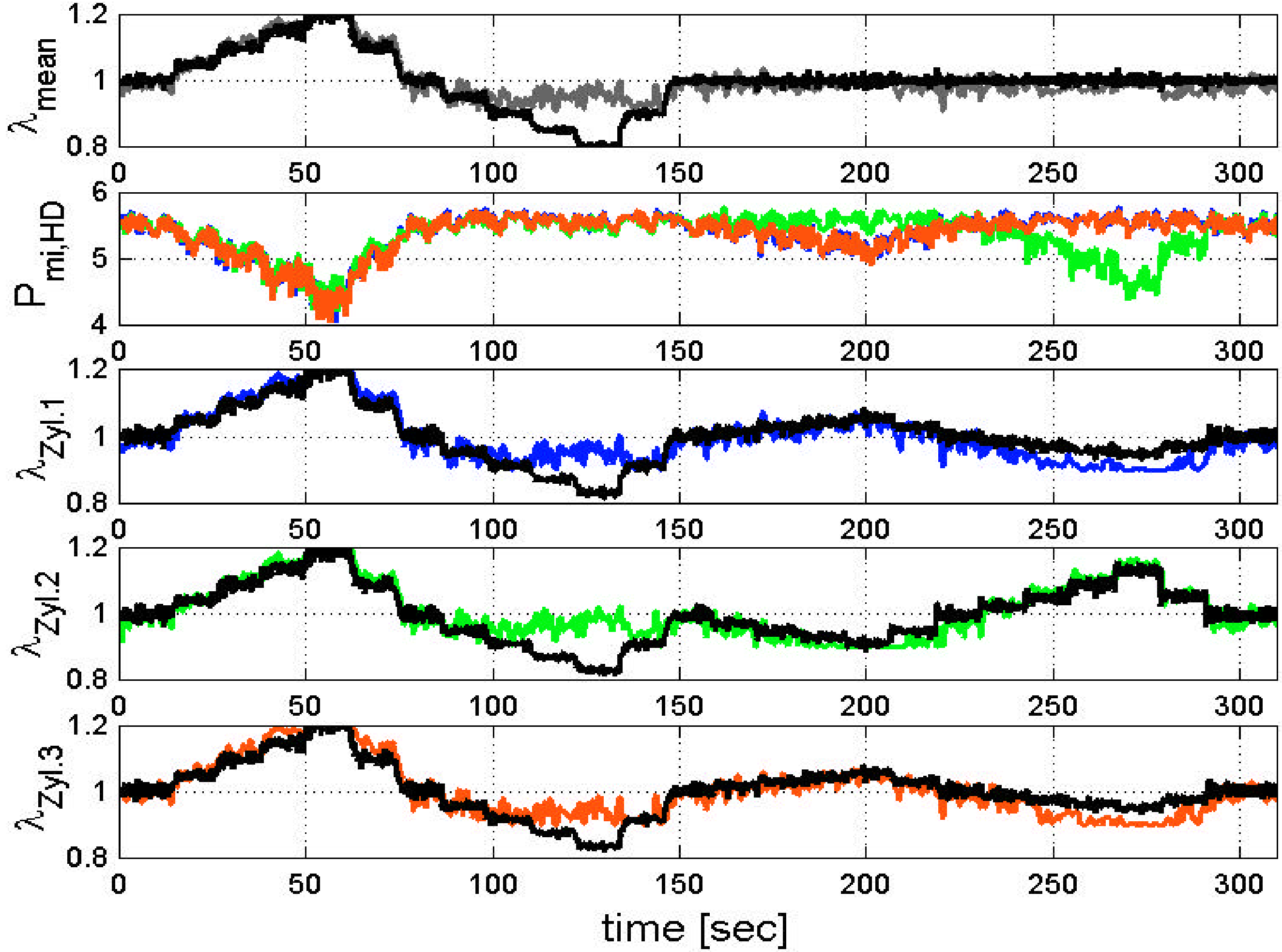
Measurement Results of A/F Ratio Estimation



operating condition:
2000 rpm,
40% load,
12% EGR,
θ_Z = 24°CA b. TDC

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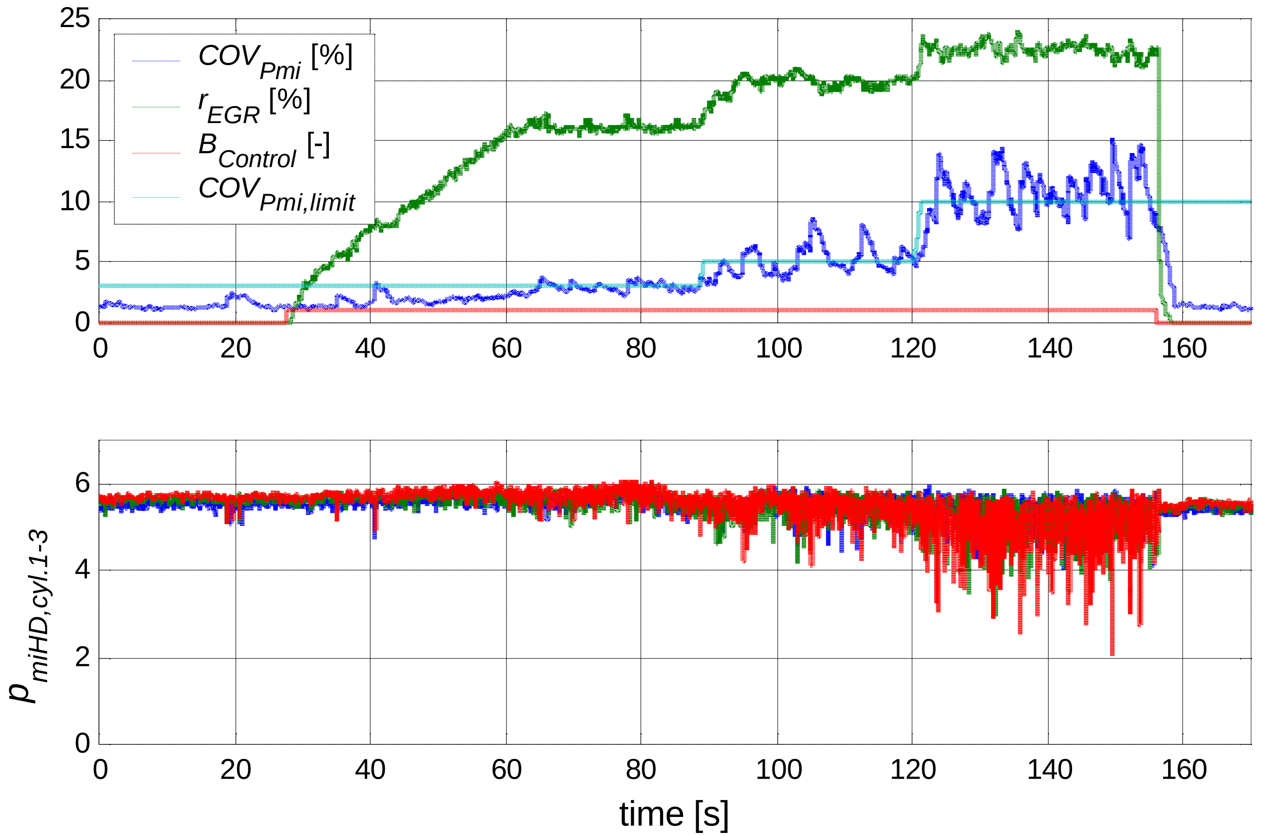
Generation of characteristic features for closed-loop control

Coefficient of Variation of indicated mean effective pressure: $COV_{p_{mi}} = \frac{s_{p_{mi}}}{\bar{p}_{mi}} \cdot 100\%$

driveability limit: $COV_{p_{mi}} = 3\% \ \ldots \ 10\%$



operating conditions:
2500 rpm,
40% load,
q_{ig} = 20-30°CA b. TDC

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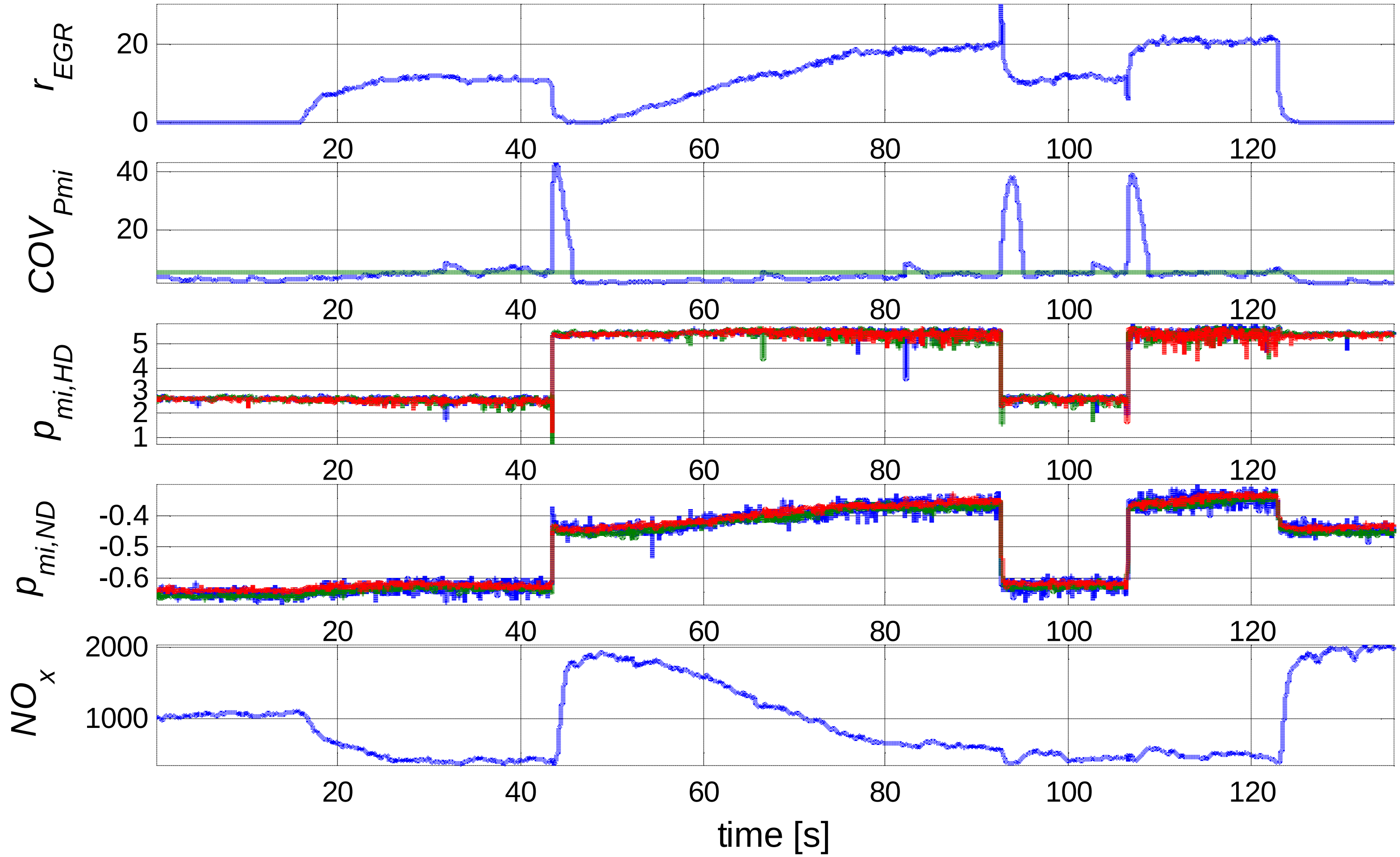
Closed-loop EGR control: measurement results



operating condition:
2500 rpm,
20-40% load

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iterative approach to calculate cylinder air charge

partial pressure quations:

$$\sum_{i=1}^{I} p_i = \sum_{i=1}^{I} (x_i \cdot p_{tot}) = p_{tot}$$

$$p_i = m_i \cdot \frac{R_i \cdot T_{tot}}{V_{tot}}$$

total cylinder charge:

$$p_{ref} = p_{Air} + p_{FV} + p_{RG} + p_{EGR}$$

measured signal

$$r_{EGR} = \frac{p_{EGR}}{p_{Air}} \cdot 100\% \Rightarrow p_{EGR}$$

$$p_{RG} = m_{RG} \cdot \frac{R_{RG} \cdot T_{ref}}{V_{ref}} \quad \text{with} \quad m_{RG} = \frac{V_c \cdot p_{TDC,GE}}{R_{RG} \cdot T_{RG}}$$

$$p_{FV} = m_{FV} \cdot \frac{R_{FV} \cdot T_{ref}}{V_{ref}}$$

$$m_{FV} = \frac{1}{14.7 \cdot l} \cdot m_{Air} = \frac{1}{14.7 \cdot l} \cdot p_{Air} \cdot \frac{V_{ref}}{R_{Air} \cdot T_{ref}}$$

$$p_{FV} = p_{Air} \cdot \frac{R_{FV}}{14.7 \cdot l \cdot R_{Air}}$$

$$\Rightarrow p_{Air} = \frac{p_{ref} - m_{RG} \cdot \frac{R_{RG} \cdot T_{ref}}{V_{ref}}}{1 + \frac{r_{EGR}}{100\%} + \frac{R_{FV}}{14.7 \cdot l \cdot R_{Air}}} \quad \text{with} \quad T_{ref} = x_{Air} \cdot T_{Air} + x_{RG} \cdot T_{RG} + x_{EGR} \cdot T_{EGR} + x_{FV} \cdot T_{FV}$$

➔ iterative calculation of T_{ref}!

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Calculation of absolute pressure and sensor offset

sensor signal:

$$U(q) = K_S \cdot p(q) + U_{bias}$$

polytropic compression:

$$p(q_i) = \left(\frac{V(q_{ref})}{V(q_i)} \right)^k \cdot p_{ref}$$

$$= c_i \cdot p_{ref}$$

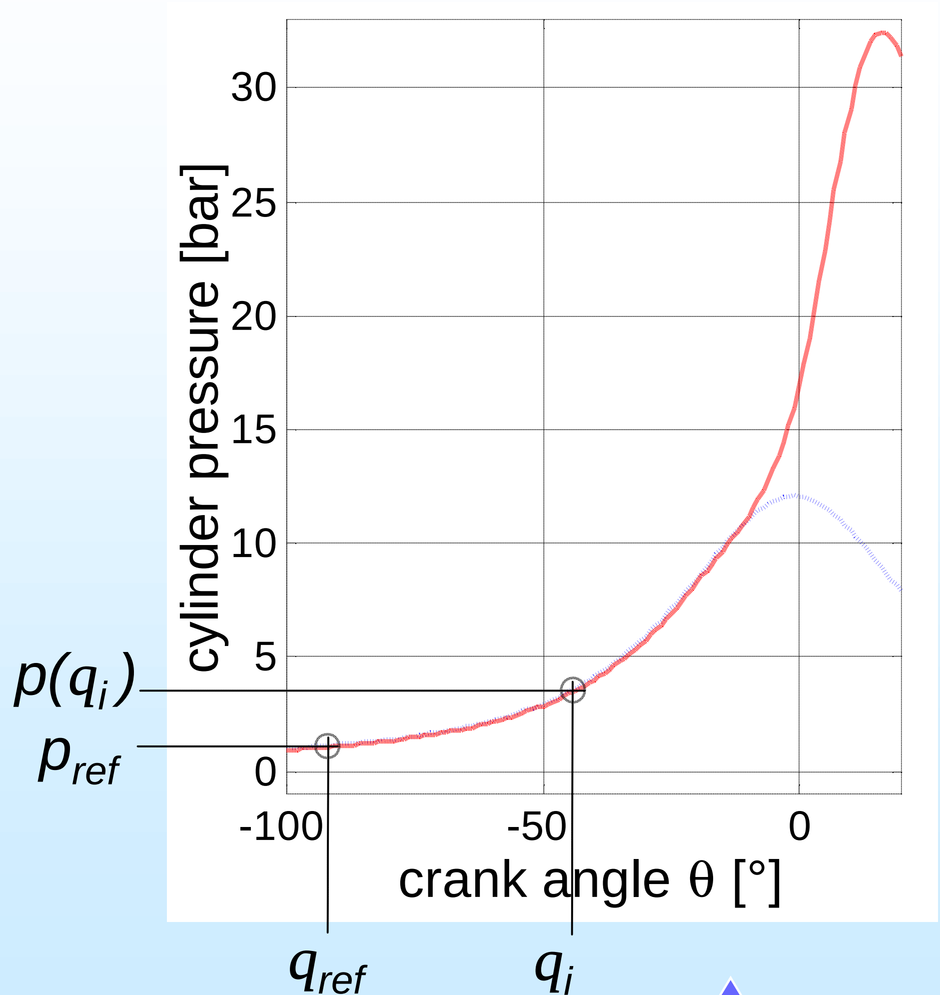
for each measurement sample:

$$U(q_i) = K_S \cdot c_i \cdot p_{ref} + U_{bias}$$

$$\rightarrow \begin{pmatrix} U(q_1) \\ U(q_2) \\ \vdots \\ U(q_N) \end{pmatrix} = \begin{pmatrix} 1 & c_1 \\ 1 & c_2 \\ \vdots & \vdots \\ 1 & c_N \end{pmatrix} \cdot \begin{pmatrix} U_{bias} \\ K_S \cdot p_{ref} \end{pmatrix}$$

$$\Leftrightarrow y = X \cdot w$$

→ LS-solution: $w = \left(X^T \cdot X \right)^{-1} \cdot X^T \cdot y$



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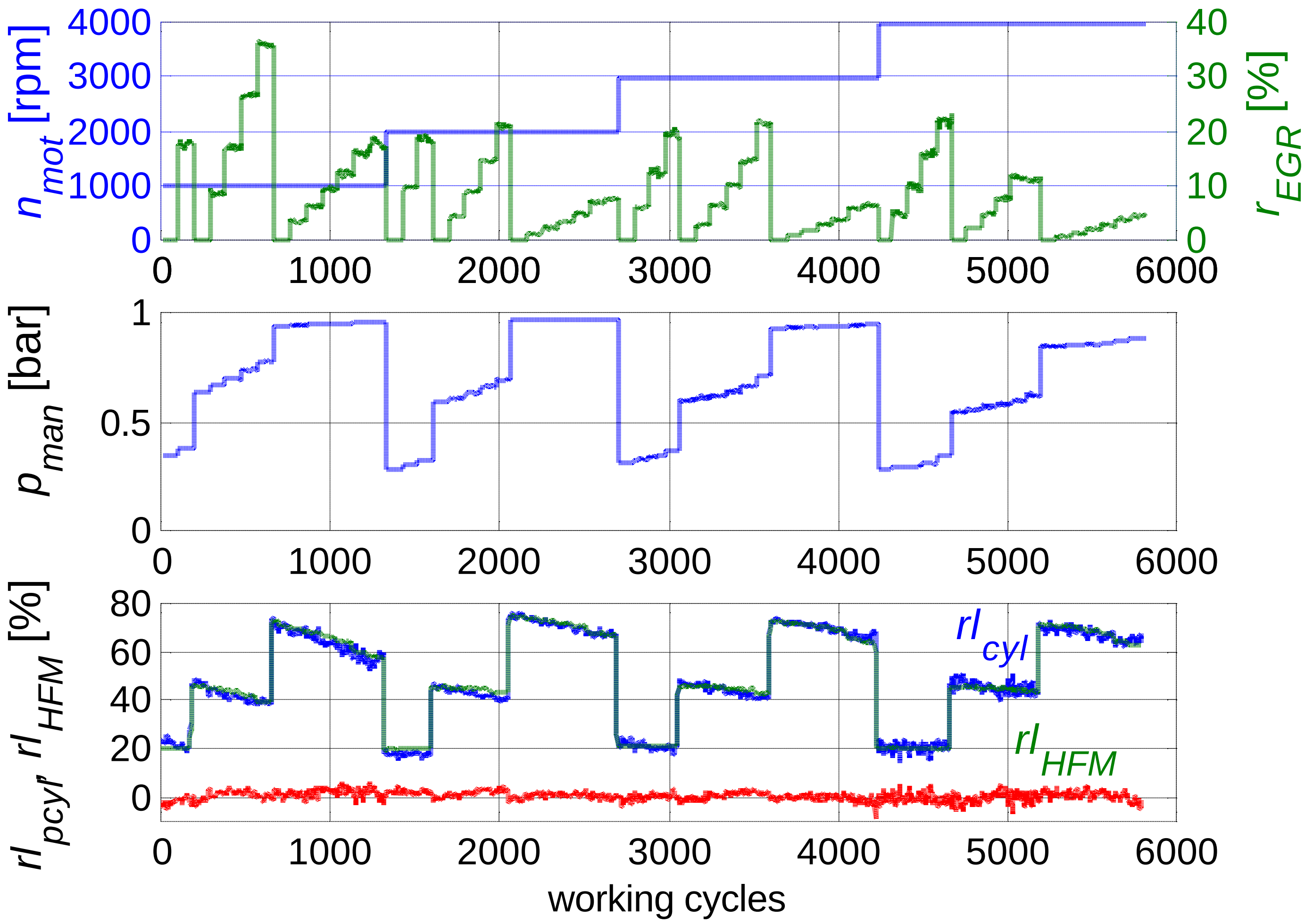
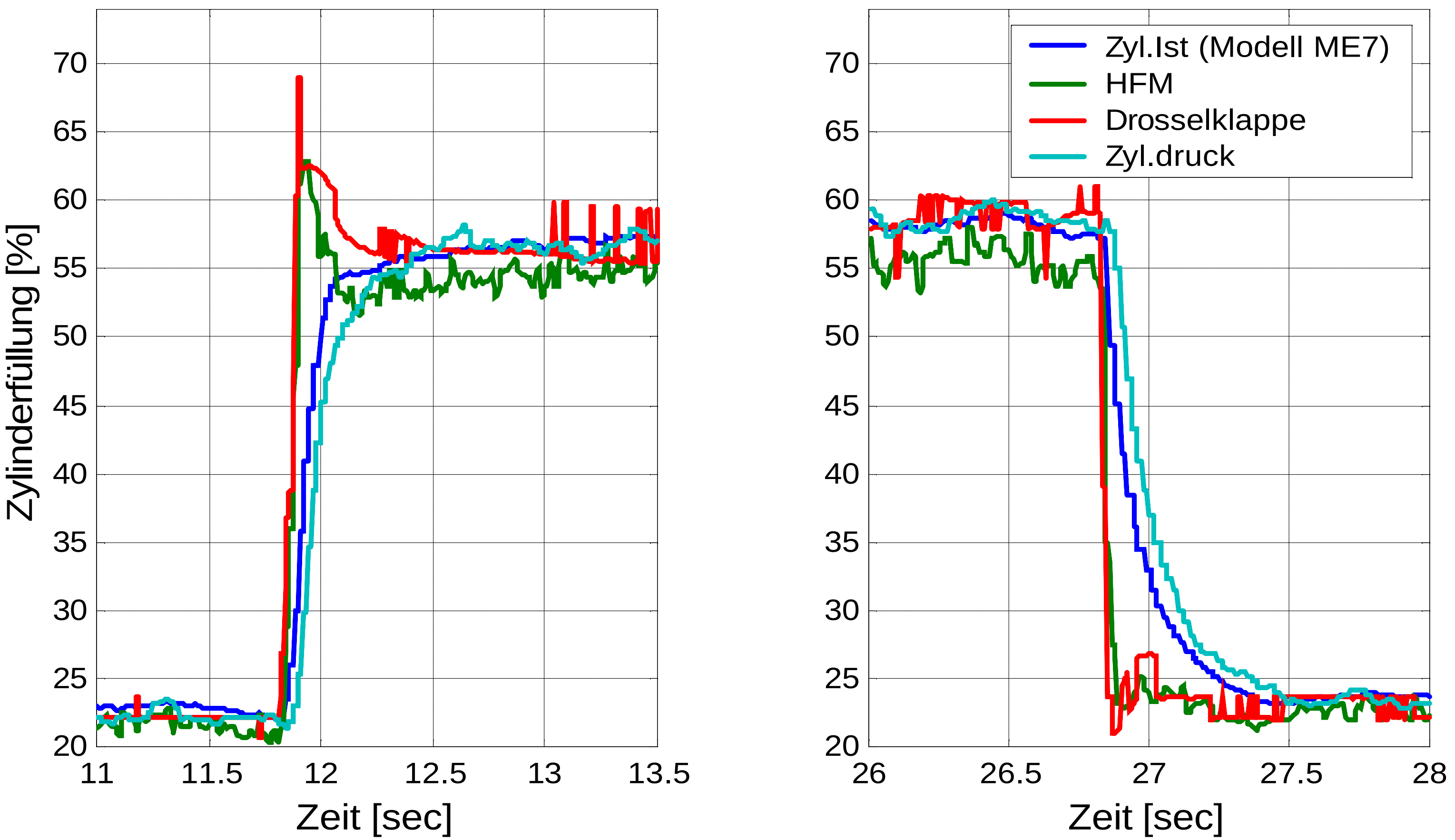
measurement results



Füllungserfassung, dynamisch



Arbeitspunkt: 2000 U/min, 0% AGR, ZZP = 25°/17°KW vor OT bei 20%/55% Füllung

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Summary

- closed-loop control of ignition timing
  - ➔ compensation for manufacturing tolerances, aging, and changing ambient conditions (fuel quality, air humidity, ...)
  - ➔ long term stability of exhaust gas emissions
  - ➔ reduced fuel consumption
  - ➔ supervision of ignition system
- air-fuel balancing
  - ➔ compensation for manufacturing tolerances and aging
  - ➔ reduced aging of catalytic converter
  - ➔ reduced emissions
- closed-loop control of EGR
  - ➔ compensation for manufacturing tolerances and aging
  - ➔ reduced fuel consumption
  - ➔ reduced NOx emissions
- measurement of indicated torque
  - ➔ misfire detection, reduced HC emissions, reduced aging of catalytic converter
- controlled air-fuel *un*balancing during warm-up
  - ➔ improved warm-up behavior
  - ➔ reduced NOx emissions
- reduction of over-fuel during cold-start by supervision of P_{mi}
  - ➔ reduced CO and HC emissions

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