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
History

1989

BOSCH: (piezo-resistive)

1986

Texas Instruments: (piezo-electric)

1988

(Honda): Ignition Control (piezo-electric, spark plug)

(Matekunas (GM): Pressure Ratio)

1980

Hubbard, Powell (Stanford): Ignition Control

1992

(Toyota): Lean-Burn Engine (piezo-resistive)

1996

(Optrand: (fibre optical)

2000

(AENEAS (Ricardo/DaimlerChrysler/Kistler) (resistive)

1976

(MTU): Peak Pressure Control (Diesel)

1994

(Opel): Cylinder Pressure Management

1989

(Honda): Ignition Control

1998

(Nissan): Ignition Control (piezo-electric, spark plug)

1990

1998 2000

1998

1. Introduction
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

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

**Reduced calibration effort**
- fault detection algorithms
- providing indicated torque signal
- misfire detection

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Dynamic Engine Test Stand

2. Experiment Environment
2. Experiment Environment

Rapid Control Prototyping and Indicating System

MATLAB/Simulink
Stateflow
Real-Time Workshop

Opel-DTI.mdl
EDC-Model

IndiSPACE.c
on-line Indicating Software

IndiSPACE.m
off-line Indicating Software

Real-Time Interface
Microtec PowerPC C Compiler

ControlDesk
MLIB / MTRACE

Host PC
ISA Bus Interface
DS813 Transmitter Board

RCP-System

PowerPC
DS1005

CAN
DS4302

MUX-A/D
DS2003

Multi-I/O
DS2201-1

Timer
DS2001

Multi-I/O
DS2201-2

DIO/PWM
DS4001

ECU Interface
DS4120

ISA BUS Interface
DS814 Receiver Board

d SPACE PX20 Box

IndiSPACE

PowerPC
DS1005

CAN
DS4302

MUX-A/D
DS2003

Timer
DS2001

RAM
DS4110

CAN, PWM

K-line
KWP 2000

cylinder pressure signals

crankshaft signal

Electronic Control Unit

Norbert Müller
TU Darmstadt
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

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Norbert Müller
TU Darmstadt

3. Closed-Loop Ignition Timing Control
Cylinder Pressure Evaluation

Compression stroke (1 → 2): \[ p \cdot V^\kappa = C_1 \]
Expansion stroke (3 → 4): \[ p \cdot V^\kappa = C_2 \]

\[ Q_B \sim C_2 - C_1 = p_{eoc} \cdot V_{eoc}^\kappa - p_{ign} \cdot V_{ign}^\kappa \]

\[ x_{MFB}(\theta) \approx \frac{p(\theta) V^\kappa(\theta) - p_{ign} V_{ign}^\kappa}{p_{eoc} V_{eoc}^\kappa - p_{ign} V_{ign}^\kappa} \]

after end of combustion:
1.) calculate \( x_{MFB}(\theta) \) for \( \theta_{ign} < \theta < \theta_{eoc} \)
2.) search \( x_{MFB}(\theta) = 0.5 \) \( \Rightarrow \theta_{MFB=0.5} \)

Constant volume diagram of ideal combustion cycle

Norbert Müller
TU Darmstadt
3. Closed-Loop Ignition Timing Control
Influence of „Location of 50%MFB“ on Indicated Engine Torque

variation of ignition timing at 2000 rpm, 35% load
Cyclic Variation of Combustion Pressure Features at Constant Operating Conditions

- Operating condition: 3000 rpm, 50% load, 0% EGR
- COV\(_{Pmi}\)=1.3%

3. Closed-Loop Ignition Timing Control
Structure of Learning Feed-Forward Ignition Timing Control

3. Closed-Loop Ignition Timing Control
Learning Feed-Forward Ignition Timing Control during load changes

3000 rpm,
0% EGR,
\[ \theta_{z,\text{conv}} \approx 26^\circ \text{ b. TDC} \]
adapted Offset-Mappings

3. Closed-Loop Ignition Timing Control
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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

4. Air-Fuel Ratio Estimation

\[ \text{air mass} \rightarrow n_{\text{mot}} \rightarrow M_{\text{opt}} \rightarrow M_i \]

\[ \lambda \rightarrow \eta_{\lambda,\text{norm}} \]

\[ \theta_{\text{opt, 50\% MFB}} \rightarrow \eta_{\theta_{50\% MFB}} \]

\[ \text{influence of} \lambda \text{ on indicated torque} \]

\[ \text{ignition timing efficiency} \]

\[ \text{crank angle location of 50\% MFB}\]
Measurement Results of A/F Ratio Estimation

- **Operating condition:**
  - 2000 rpm,
  - 40% load,
  - 12% EGR,
  - $\theta_z = 24^\circ$CA b.

4. Air-Fuel Ratio Estimation
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Generation of characteristic features for closed-loop control

Coefficient of Variation of indicated mean effective pressure: \[\text{COV}_{p_{mi}} = \frac{\sigma_{p_{mi}}}{\bar{p}_{mi}} \cdot 100\%\]

Driveability limit: \[\text{COV}_{p_{mi}} = 3\% \ldots 10\%\]

Operating conditions:
- 2500 rpm,
- 40\% load,
- \(\theta_{ig} = 20-30^\circ\text{CA} \text{ b. TDC}\)

5. Exhaust gas recirculation control
5. Exhaust gas recirculation control

Operating condition: 2500 rpm, 20-40% load
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iterative approach to calculate cylinder air charge

Partial pressure equations:
\[
\sum_{i=1}^{l} p_i = \sum_{i=1}^{l} (x_i \cdot p_{tot}) = p_{tot}
\]

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

Total cylinder charge:
\[
p_{ref} = p_{Air} + p_{FV} + p_{RG} + p_{EGR}
\]

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

\[
p_{FV} = m_{FV} \cdot \frac{R_{FV} \cdot T_{ref}}{V_{ref}} \quad \text{with} \quad m_{FV} = \frac{1}{14.7 \cdot \lambda} \cdot m_{Air} = \frac{1}{14.7 \cdot \lambda} \cdot p_{Air} \cdot \frac{V_{ref}}{R_{Air} \cdot T_{ref}}
\]

\[
p_{FV} = p_{Air} \cdot \frac{R_{FV}}{14.7 \cdot \lambda \cdot R_{Air}}
\]

\[
p_{Air} = \frac{p_{ref} - m_{RG} \cdot \frac{R_{RG} \cdot T_{ref}}{V_{ref}}}{1 + \frac{r_{EGR} \cdot 100%}{14.7 \cdot \lambda \cdot R_{Air}}}
\]

\[
T_{ref} = x_{Air} \cdot T_{Air} + x_{RG} \cdot T_{RG} + x_{EGR} \cdot T_{EGR} + x_{FV} \cdot T_{FV}
\]

\[
\Rightarrow \text{iterative calculation of} \ T_{ref}!
\]

6. Calculation of cylinder gas components
sensor signal:
\[ U(\theta) = K_s \cdot p(\theta) + U_{bias} \]

polytropic compression:
\[ p(\theta_i) = \left( \frac{V(\theta_{ref})}{V(\theta_i)} \right)^k \cdot p_{ref} = c_i \cdot p_{ref} \]

for each measurement sample:
\[ U(\theta_i) = K_s \cdot c_i \cdot p_{ref} + U_{bias} \]

\[
\begin{pmatrix}
U(\theta_1) \\
U(\theta_2) \\
\vdots \\
U(\theta_N)
\end{pmatrix} = \begin{pmatrix} 1 & c_1 \\ 1 & c_2 \\ \vdots & \vdots \\ 1 & c_N \end{pmatrix} \begin{pmatrix} U_{bias} \\ K_s \cdot p_{ref} \end{pmatrix}
\]

\[ \iff \quad y = X \cdot w \]

\[ \iff \quad \text{LS-solution:} \quad w = \left( X^T \cdot X \right)^{-1} \cdot X^T \cdot y \]

6. Calculation of cylinder gas components
measurement results

6. Calculation of cylinder gas components
Füllungserfassung, dynamisch

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

6. Calculation of cylinder gas components
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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 fuel consumption
  - reduced NOx emissions
  - 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 unbalancing 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