Dynamic Matrix Control for Emission Control of a Diesel Engine

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Christian Kozlik, AVL List GmbH

Presented by: Alexander Schirrer, Vienna University of Technology
Contents

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  - Status quo of engine calibration
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- Emission control concept by Dynamic Matrix Control (DMC)
- Extensions
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  - Data reduction
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  - Improvement on fast load transients
- Conclusions
Overview

- Status quo of engine calibration
- Introduction of Model Predictive control (MPC)

Emission control concept by Dynamic Matrix Control (DMC)

Extensions

- Engine nonlinearities
- Data reduction
- Actuator and operational constraints
- Improvement on fast load transients

Conclusions
Overview

Status quo of engine calibration (1)

- Closed loop control of
  - Boost pressure
  - Air mass
  - ...

- Calibration of maps for
  - Demand values
  - Pre control values
  - Further inputs:
    - injection timings, pilot / post quantities, ...

PID controllers

\[
\sum K_p \cdot e(t) - K_i \cdot \int e(t) dt - K_d \cdot \frac{de(t)}{dt} \rightarrow \text{Process}
\]
Overview

Status quo of engine calibration (2)

- Targets:
  - Emissions
  - Fuel consumption
  - ...

→ In specific driving cycles and operating areas
Overview

Model predictive control (MPC)

- Replacement of PID controllers with MPC
  - Basic control setup remains unchanged

- MPC features:
  - Utilization of simplified models of the controlled system
    - Dynamic behavior of the engine is known to the MPC:
      - MPC can optimize the actuator movements accordingly
  - Predictive control:
    - Actuators can be moved earlier
    - Faster / more accurate / more aware control
Overview

Model predictive control (MPC)

- Replacement of PID controllers with MPC
  - Basic control setup remains unchanged

- MPC features:
  - Utilization of simplified models of the controlled system
  - Consideration of input and output constraints
Overview

Model predictive control (MPC)

- Replacement of PID controllers with MPC
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- MPC features:
  - Utilization of simplified models of the controlled system
  - Consideration of input and output constraints
  - MIMO control
    - e.g. coupled boost pressure **AND** air mass control
Model predictive control (MPC)

- Replacement of PID controllers with MPC
  - Basic control setup remains unchanged

- MPC features:
  - Utilization of simplified models of the controlled system
  - Consideration of input and output constraints
  - MIMO control
  - Feed back or feed forward operation possible
Overview

Model types in MPC:

- Typical models used in engine control:
  - State space
  - Neuronal networks
  - Mean values models

- Chosen approach, novel for engine control:
  - Step response models
    - Dynamic Matrix Control (DMC)
    - Proven concept in process and chemical industry
      - characterized by rather slow processes
Overview

Adaptation of DMC for engine control

- Applied for emission control
  - MIMO control of soot and NO$_x$

- Challenges:
  - Fast processes in a combustion engine
  - Strongly nonlinear engine behavior

Inputs:
- EGR valve
- Injection timing
- Rail pressure

Outputs:
- Soot
- NO$_x$
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**DMC Control Principle**

**Objective function:**

\[
J = E \left\{ \sum_{i=1}^{N_p} [\hat{y}(k+i) - y_{ref}(k+i)]^T Q_y(i)[\hat{y}(k+i) - y_{ref}(k+i)] \right\} + \sum_{j=0}^{N_c-1} \Delta u^T(k+j)R_u(j)\Delta u(k+j)
\]

- **Control error** \( e \)
- **Weighting factors on control error**
- **Input rates**
- **Weighting factors on input rates**

**Tuning parameters:**

- \( N_p \) ... prediction horizon
- \( N_c \) ... control horizon
- \( T_s \) ... sampling time
- \( Q_y, R_u \) ... weighting factors

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DMC Control Principle

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\]

\[
u^{min} \leq u(k) \leq u^{max}
\]

\[
\Delta u^{min} \leq \Delta u \leq \Delta u^{max}
\]
**DMC Control Principle**

![Diagram of DMC Control Principle]

**Predicted outputs:**

\[
\hat{Y} = H \Delta U^+ + P \Delta U^- + Y
\]

- \( \hat{Y}(k + 1|k) \)
- \( \hat{Y}(k + 2|k) \)
- \( \hat{Y}(k + N_p|k) \)

**Tuning parameters:**

- \( N_p \) ... prediction horizon
- \( N_c \) ... control horizon
- \( T_s \) ... sampling time
- \( Q_y, R_u \) ... weighting factors

**Step response matrix**

**Free response matrix**

**Future and past input rates**

**Current outputs**
**DMC Control Setup**

Setup of a hierarchical control scheme:

- External torque control
- DMC for emission control
- Mean value engine model

![Diagram of DMC Control Setup]

- External inputs:
  - Engine speed
  - Torque demand
  - Soot demand
  - NO\textsubscript{x} demand

- Feedback:
  - Torque measured
  - Soot measured
  - NO\textsubscript{x} measured

- Control variables:
  - Fuel
  - EGR valve
  - SOI
  - Rail pressure

- External torque control
- DMC for emission control
- Mean value engine model
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Consideration of Nonlinearities

Influences on nonlinear engine behavior:

- Operating point:

  - Inputs:
    - Coolant temperature

  \[ N \text{Trq} \]

  \[ \text{Time [sec]} \]

  \[ \text{Water temperature [°C]} \]

  → Solution: Identification of models for different operating conditions
Consideration of Nonlinearities

Scheduling of step response models:

Dependencies:

• Engine speed
Consideration of Nonlinearities

Scheduling of step response models:

Dependencies:

- Engine speed
- Torque
Consideration of Nonlinearities

Scheduling of step response models:

Dependencies:
- Engine speed
- Torque
- EGR valve
Consideration of Nonlinearities

Scheduling of step response models:

Dependencies:
- Engine speed
- Torque
- EGR valve
Consideration of Nonlinearities

Scheduling of step response models:

→ Benefit:

*Fast and accurate* control for any operating conditions

Dependencies:
- Engine speed
- Torque
- EGR valve
- Timing
- Rail pressure
- Coolant temperature

6 dimensions
Consideration of Nonlinearities

Example: Application of DMC in the NEDC including the warm-up phase:

Coupled control of soot and NO\textsubscript{x}

Inputs:

- EGR valve
- Injection timing
- Rail pressure

Warm-up modeled by means of simplified physical model
Consideration of Nonlinearities

Example: Application of DMC in the NEDC including the warm-up phase:

Coupled control of soot and NO\textsubscript{x}

Accumulated control errors of soot and NO\textsubscript{x}

DMC, step resp. 25°C - 90°C
DMC, step resp. 90°C
Reduction of Stored Data

Influences on amount of stored data:

- Prediction horizon
  - $N_p$
- Sampling time
  - $T_s$
- Number of inputs / outputs
  - $u$, $y$

→ Reduction possible by parameterization of the step response models
Reduction of Stored Data

Approximation of the step responses by transfer functions:

\[ tf = \frac{as + b}{cs^2 + ds + 1} \]

Fitting by least squares minimization

- Recorded step response
- Parameterized step response

Data reduction: - 92 %
Actuator Constraints

DMC optimizes under given actuator (input) constraints:

\[ J = E \left\{ \sum_{i=1}^{N_p} \left[ \hat{y}(k+i) - y_{ref}(k+i) \right]^T Q_y(i) \left[ \hat{y}(k+i) - y_{ref}(k+i) \right] \right\} + \sum_{j=0}^{N_a-1} \Delta u^T(k+j) R_u(j) \Delta u(k+j) \]

\[ u^{min} \leq u(k) \leq u^{max} \quad \rightarrow \quad \text{Absolute input values} \]

\[ \Delta u^{min} \leq \Delta u \leq \Delta u^{max} \quad \rightarrow \quad \text{Rate of change} \]

Benefit over classic PID:

→ No external saturations

→ No anti-windup strategy required
Actuator Constraints

DMC optimizes under given actuator (input) constraints:

Example:

- Control of NO$_x$
- Input: EGR valve position

Demand

- $u^{\text{max}} = 100\%$, $\Delta u^{\text{max}} = 500\%/s$
- $u^{\text{max}} = 50\%$, $\Delta u^{\text{max}} = 500\%/s$
- $u^{\text{max}} = 50\%$, $\Delta u^{\text{max}} = 20\%/s$
**Operational Constraints**

Additional constraints on inputs:

→ Avoid certain areas of operation

→ e.g. excess of HC emissions with:
  - High EGR rate and
  - Retarded injection timing

\[ Au \leq \gamma \]

Influence of inputs on HC formation

Given soot demand can be achieved with various input combinations
Operational Constraints

Example: Soot control with 2 inputs

→ High HC formation can be avoided
→ Still the soot demand is reached
Compensation of Dynamic Torque Transients

Dynamic load changes can affect the control massively:

Example:

- Soot control in dynamic part of NEDC
- Input: EGR valve position

![Graph showing vehicle speed, engine speed, torque, soot, and EGR valve percentage over time.]

Christian Kozlik, AVL List GmbH
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Compensation of Dynamic Torque Transients

Dynamic load changes can affect the control massively:

Example:

- Soot control in dynamic part of NEDC
- Input: EGR valve position

Large soot peaks caused by:

- High EGR rate plus increase of injected quantity
- Low excess air ratio

→ Influences of dynamic load change are not modeled in the recorded step responses
Compensation of Dynamic Torque Transients

Dynamic load changes can affect the control massively:

Improvement:

→ Input of future torque demand to DMC
Compensation of Dynamic Torque Transients

Dynamic load changes can affect the control massively:

**Improvement:**

→ Input of future torque demand to DMC

→ Recording of additional torque step responses
Compensation of Dynamic Torque Transients

Dynamic load changes can affect the control massively:

**Improvement:**

- Input of future torque demand to DMC
- Recording of additional torque step responses
- Predicted outputs become:

\[
\hat{Y} = H\Delta U^+ + P\Delta U^- + Y \\
+ H_z\Delta Z^+ + P\Delta Z^-
\]
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Conclusions

- Successful introduction of DMC in engine control
  - Model-based, predictive MIMO control of emissions successful
  - Simple modeling and parameterization

- Extensions:
  - Addressing system nonlinearities via parameterized models
  - Considering actuator and operational constraints
  - Compensating impact of fast torque transients on emissions

- Predictive control feasible, high control performance achieved

- Outlook:
  - Implementation in a real engine and ECU promising and feasible
Thank you for your attention!