Diploma Thesis:

Advanced Fuel to Air Ratio Control for Reciprocating Legacy Natural Gas Engines

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Abstract

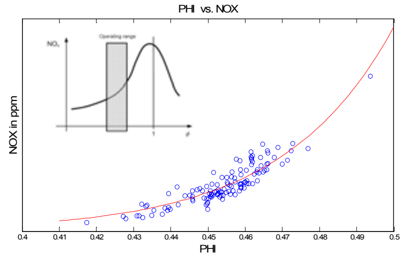
The governmental regulations concerning emissions of fossil fuel powered engines are more and more strengthened. New laws are focusing especially on nitrogen oxide and nitrogen dioxide emissions (NOx). Not only car engines are affected by strong emission restrictions, but also industrial engines. Several techniques are known to reduce the NOx emissions, especially an advanced fuel to air ratio (PHI) control is known as major step towards further emission reduction. The possibility to reduce the NOx emissions was investigated for legacy reciprocating natural gas powered engines. This kind of engine is used on pipeline pump stations. The typical control on such pipeline engines consists of nested SISO PID loops. The system has naturally a MIMO structure. A MIMO control can use the information about the coupling to improve the overall control performance. Two MIMO model based controller, which inherently take into account the couplings, were designed. By simulation, the control performance was compared with the SISO control performance. The most promising approach – a model predictive control (MPC) – was implemented on the real engine. Focusing on the squared PHI deviation over 80 % reductions were achieved.

Introduction:

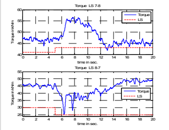
Main aim → Reduce NOx on existing engines

- Advanced fuel mixing
- Ignition timing
- Catalytic reduction
- Low emission engine design

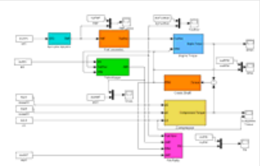
$$\phi = stoich \cdot \frac{Fuelmass}{Airmass}$$



- 6 cylinder two stroke engine
- 2000hp @ 300 rpm
- Powered with natural gas (GFC → RPM)
- Turbo charged (WG→AMP)
- Drives 3 compressor cylinders
- Power control is done with pockets
- Pockets → additional compressor clearance volume
- 28 different combinations → Load Steps (LS)
- Not perfectly synchronized switching
    - Substantial load deviations
    - Disturbance very crucial
    - Causes peaks in the emissions



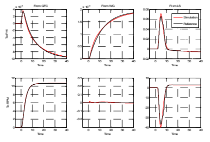
Simulation Model / Models for Control



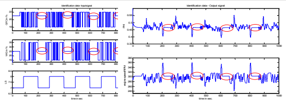
- MIMO state space system
- PEM
- 6th order
- Ta = 0.1s
- Time delays
    - GFC 0.6s
    - WG 1.1s
    - LS 2.3s

$$x_{k+1} = A \cdot x_k + B \cdot \begin{bmatrix} GFC \\ WG \\ LS \end{bmatrix}$$

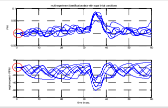
$$\begin{bmatrix} PHI \\ RPM \end{bmatrix} = C \cdot x_k$$



Excitation signal with constant parts:

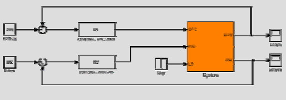


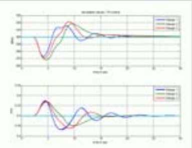
→ Multi experiment with equal initial conditions :



- Approximation of load deviation by dynamic model
- Each LS changes has a different load deviation → different models
- Split data stream according to LS situation → multi experiment with equal initial conditions

SISO PI - Control

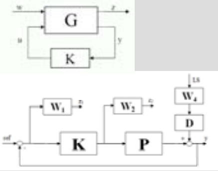




- **Chien, Hrones and Reswick design guide**
- **3 different proportional parts**

$\mathcal{H}_\infty$ Control

- Inputs
    - o Exogenous input w
        - References
        - Disturbances
    - o Manipulated variables u
- Outputs
    - o Performance output z
        - E.g. tracking error
    - o Measured variables y



Optimal Control Performance

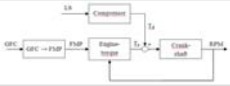
- What is the optimal control performance?
- Is it possible to achieve optimal tracking with constraints on *GFC* and *WG*?

$$Optimal\ Tracking:$$

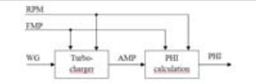
$$J_{track} = \sum c_1 \cdot ePHI^2 + c_2 \cdot eRPM^2 = 0$$

⇨ Invert system dynamic

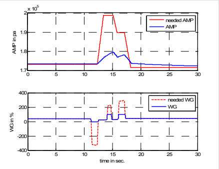
1. Invert GFC → RPM Path



2. Invert WG→ PHI Path



Result :



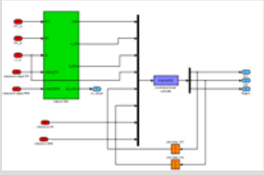
- Turbocharger not fast enough
- Always a compromise between PHI and RPM deviation

Model Predictive Control

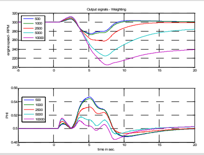
- Identify a linear model for MPC
- Extend the state space
    - Manipulated variables (GFC,WG)
    - Measured disturbances (LS)
    - Offset free tracking
    - Future measured disturbance
- Calculate online version of MPC with MPC Toolbox
- Calculate explicit MPC
    - Hybrid Toolbox
    - Generate C-header
    - Modification of MPC object necessary
    - Result → state regulator
- Design Kalman filter
- Implement MPC in Simulink →dSpace

$$\begin{bmatrix} x_{e,k+1} \\ v_{k+1} \\ e_{k+1} \end{bmatrix} = \begin{bmatrix} A & E & 0 \\ 0 & I & 0 \\ 0 & 0 & I \end{bmatrix} \cdot \begin{bmatrix} x_{e,k} \\ v_k \\ e_k \end{bmatrix} + \begin{bmatrix} B \\ 0 \\ 0 \end{bmatrix} \cdot u_k$$

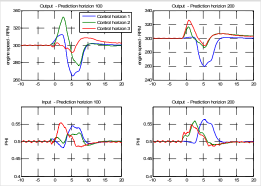
$$y_k = \begin{bmatrix} C & 0 & I \end{bmatrix} \cdot \begin{bmatrix} x_{e,k} \\ v_k \\ e_k \end{bmatrix}$$



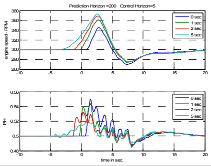
Weighting on PHI and RPM



Prediction / Control horizon

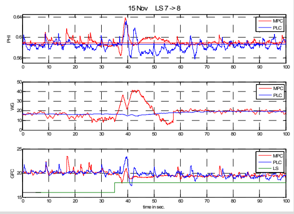


Future disturbance information:



Field Test

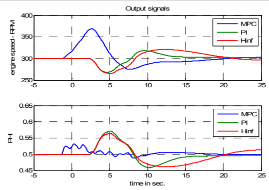
- The MPC approach was implemented as real time application running on a dSpace AutoBox.
- Explicit approach with control horizon = 1
- 3 MPC according to the LS situation (LS 7→8, LS 8→7, small LS)



Squared PHI deviation

LS change	MPC (PLC=100%)
7 → 8	63 %
8 → 9	27.2 %
9 → 10	43.4 %
10 → 9	19.1 %
9 → 8	35.1 %
8 →7	70.5 %
average	57 %

Comparison



- $\mathcal{H}_\infty$ controller tuning very challenging, result not satisfying
- PI control easy to tune, result comparable with $\mathcal{H}_\infty$
- MPC tuning very flexible, best performance

Conclusions

- Reduce and keep PHI constant → reduces NOx Emissions
- Load deviation caused by the unsynchronized pocket switching was approximated by a dynamic system.
- Design of experiment is a very crucial
- Perfect tracking with constraints on WG is not possible
- $\mathcal{H}_\infty$ approach does not gain any advantage
- Future measured disturbance approach increases the control performance, drawback of this method is the high dimension of the system
- MPC is able to reduce squared PHI deviation up to 80%.
- Average improvement based on LS 7-10-7 : 57%

Outlook

- Turbocharger response too slow
    - → Jet assist
- Design of Experiment (DOE) very important
    - → Optimized excitation signal
    - → PRBS amplitude and frequency
- LS in truth a nonlinear parameter jumping system
    - → Nonlinear MPC instead of explicit linear MPC

$$\xi = f(LS, t)$$

$$x_{k+1} = A(\xi) \cdot x_k + B(\xi) \cdot u_k$$

$$y_k = C(\xi) \cdot x_k + D(\xi) \cdot u_k$$