Institute for Design and Control of Mechatronical Systems

Diploma Thesis:

Nonlinear Model Predictive Control for a Diesel Engine Airpath

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Abstract

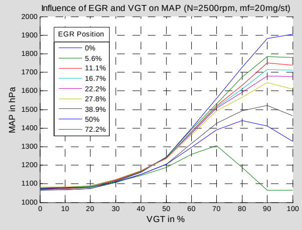
In today's society, passenger cars play an important role as most widespread means of transportation. As a consequence, the number of cars driving along the roads increases every year. In Austria, especially the number of vehicles powered by diesel engines rises continuously. But more cars also cause more air pollution. So the government restricts the permitted emissions in periodically intervals to lower levels.

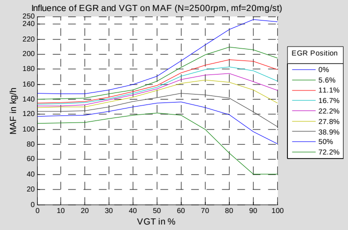
This is the main reason for car manufacturer to work persistently on the improvement of modern engines. The aim is to reduce emissions while the demand for available power increases. Several inventions, basically concerning diesel engines, like exhaust gas recirculation (EGR) and variable geometry turbochargers (VGT) made this progress possible. But further restrictions on emissions will call for improved engine control structures too.

The aim of this diploma thesis is to design a Nonlinear Model Predictive Controller (NMPC) for the airpath control of a diesel engine equipped with two actuators, called exhaust gas recirculation (EGR) valve and variable geometry turbocharger (VGT). Therefore, a suitable model structure for an output prediction model, which is required by the NMPC, must be investigated. Hence, two different modelling techniques are studied. A model structure mainly based on physical equations, named Mean Value Model (MVM) on the one side, and a databased technique for the creation of a so called Linear Parameter Varying (LPV) model on the other side. The required computational power for the online calculation of the manipulated variables is the limiting factor in this engine control application.

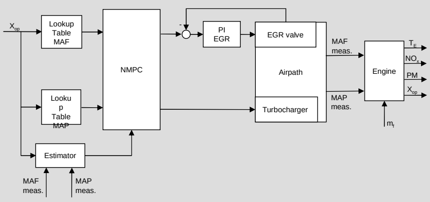
This nonlinear approach is intended to characterise the airpath behaviour in the engine's whole operation area by means of one plant/controller combination only, in distinction to a previous work where several linear models/controller combinations were used. This work already showed that a further reduction of engine emissions is possible by applying alternative, more efficient control structures.

Nonlinearities involving EGR and VGT

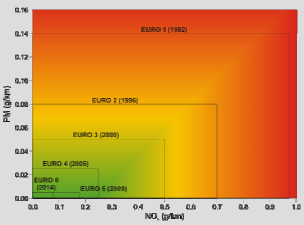




MIMO airpath control structure

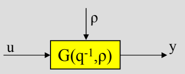


European emission standards for Diesel Engines



Airpath model

I/O LPV Identification



The I/O LPV model structure can be interpreted as a transfer function with varying coefficients which are influenced by one or more external parameters ρ to describe a nonlinear behaviour of the plant.

$$G\left(q^{-1},\rho\right)=\frac{B\left(q^{-1},\rho\right)}{A\left(q^{-1},\rho\right)}$$

$$A(q^{-1},\rho_k)\,y(k)=B(q^{-1},\rho_k)\,u_k+m_k$$

$$A(q^{-1},\rho_k)=1+a_1(\rho_k)\,q^{-1}+\ldots+a_{n_a}(\rho_k)\,q^{-n_a}$$
$$B(q^{-1},\rho_k)=b_1(\rho_k)\,q^{-1}+\ldots+b_{n_b}(\rho_k)\,q^{-n_b}$$

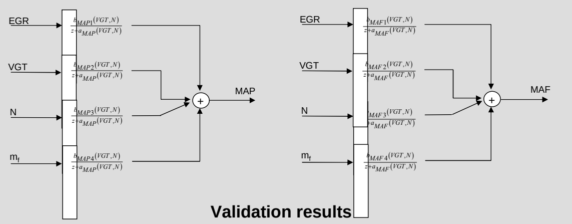
$$a_i(\rho_k)=a_i^1\,f_1(\rho_k)+\ldots+a_i^N\,f_N(\rho_k)$$

$$\varphi_k=\left[-y_{k-1}\quad -y_{k-2}\ldots-y_{k-n_a}\ \ldots u_{k-1}\quad u_{k-2}\ldots u_{k-n_b}\right]$$
$$\vartheta^i=\left[a_1^i\quad a_2^i\ldots a_{n_a}^i\quad b_1^i\quad b_2^i\ldots b_{n_b}^i\right]^T$$
$$F_k=\left[1\quad f_1(\rho_k)\ldots f_{N-1}(\rho_k)\right]$$
$$\Gamma_k=\left(F_k\otimes\varphi_k\right)$$

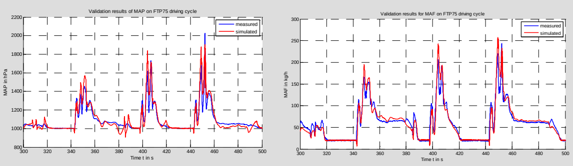
With this notation the LPV model can be identified with a modified version of a standard Least Squares Identification algorithm.

$$y_k=\Gamma_k\Theta+m_k$$

LPV airpath model structure



Validation results



Nonlinear Model Predictive Control

Cost function

$$\min_u\ \frac{1}{2}\sum_{i=0}^{NPH}\left[\left(y_i-y_{ref}\right)^T Q\left(y_i-y_{ref}\right)+u_i^T R u_i\right]$$

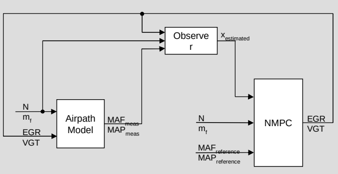
$$\begin{aligned}
s.t.\quad & x_{i+1}=A_i x_i+B_i u_i+Zv & \underline{x}\le x_i\le\overline{x} & \quad\forall i=0\ldots NPH\\
& y_i=C_i x_i & \underline{u}\le u_i\le\overline{u} & \quad\forall i=0\ldots NCH-1\\
& x_0\ \text{given} & u_i=0 & \quad\forall i=NCH\ldots NPH
\end{aligned}$$

Airpath output prediction model

$$\begin{bmatrix}x_{k+1}\\u_{k+1}\\e_{k+1}\end{bmatrix}=\begin{bmatrix}A&B&0\\0&I&0\\0&0&I\end{bmatrix}\cdot\begin{bmatrix}x_k\\u_k\\e_k\end{bmatrix}+\begin{bmatrix}0&Z\\I&0\\0&0\end{bmatrix}\cdot\begin{bmatrix}\Delta u_k\\v_k\end{bmatrix}$$

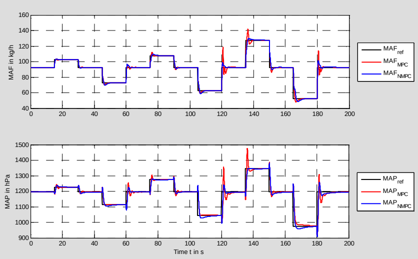
$$y_k=\begin{bmatrix}C&0&I\end{bmatrix}\cdot\begin{bmatrix}x_k\\u_k\\e_k\end{bmatrix}$$

NMPC control structure

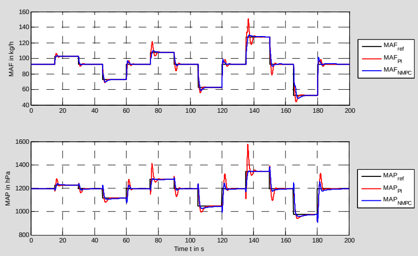


Controller validation

Comparison NMPC - MPC



Comparison NMPC - PI



Conclusions

LPV model

1. Sufficient accuracy for airpath control task
2. Less calculation effort compared to other model structures, e.g. Mean Value Model
3. Can be treated as linear system with coefficient update
4. I/O LPV model can only handle SISO and MISO structures
5. Modified Version of Least Squares Identification Algorithm can be applied
6. Determination of dependency on external parameter ρ is time-consuming

NMPC controller

1. Good tracking results
2. One plant/controller combination for whole operation area
3. Required computational power allows real time application
4. Numerical problems in some regions of the operation area

Outlook

LPV model

1. Further improvement of model quality
2. Inclusion of swirl flap as third actuator could improve impacts on emissions
3. Creation of State-Space LPV model for the consideration of different dynamics for each system input

NMPC controller

1. Real time application at test bench
2. Investigation of influences on emissions during a driving cycle
3. Alternative QP-solver for the reduction of numerical problems