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Mrosek, Frankfurt am Main

Nr. 803

Model-Based Control of a Turbocharged Diesel Engine with High- and Low-Pressure Exhaust Gas Recirculation

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Institut für
Automatisierungstechnik
und Mechatronik
der TU Darmstadt

Model-Based Control of a Turbocharged Diesel Engine with High- and Low-Pressure Exhaust Gas Recirculation

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"Model-Based Control of a Turbocharged Diesel Engine with High- and Low-Pressure Exhaust Gas Recirculation" presents the complete scope for a model-based control design with regard to the control objective dynamical driving cycle emissions. A semi-physical air path model delivers system properties of the controlled system. Experimental models for stationary and dynamical engine raw emissions are the base for stationary and dynamical optimisations of emissions and engine torque and allow to motivate deviations between stationary and dynamical emission formation. The control concept directly incorporates semi-physical relationships and model parameters of the air path model for control of HP-EGR, LP-EGR and charging pressure. The control performance is rated with quantified stationary and dynamical contributions to the overall driving cycle emissions. All models and control methods have been experimentally parameterised and validated at an engine test bench.

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Preface

This dissertation is the outcome of my time as research associate at the Institute of Automatic Control and Mechatronics at Technische Universität Darmstadt. It has been supervised by Prof. Dr.-Ing. Dr. h. c. Rolf Isermann, head of the Research Group Control Systems and Process Automation.

First of all, I would like to express my sincere gratitude to Prof. Dr.-Ing. Dr. h. c. Rolf Isermann for offering me the opportunities for my research and to write this dissertation. I felt very pleased with the high degree of responsibility that Prof. Isermann granted to me. That allowed a self dependent research, which resulted in this dissertation and shaped my personal development in an entirely positive sense. In particular, I thank Prof. Isermann for the chances to present my scientific results on national and international conferences.

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Above all, I would to express my sincere gratitude to my parents for their unconditional support during my whole education, which was the foundation for everything else. I am indebted to my wife Dr. med. dent. Friederike Mrosek, for all her patience and support during the research work.

Frankfurt am Main, March 2017
Matthias Patrick Alexander Mrosek

to Friederike, Jonathan and Theodor

Contents

Symbols and Abbreviations

Symbols

General Letter Symbols

Symbol	**Explanation**
e	error
EM	extrapolation measure
G	transfer function
J	loss function, quality criterion
k	discrete time
k	factor
M	number of local models
n	number of data points
p	number of model inputs
q	number of model outputs
q^{-1}	time delay operator: $x\,(k-1) = q^{-1}x\,(k)$
R^2	coefficient of determination
s	Laplace operator
T or τ	time constant
T_d	dead time
u	process input, input variable
$\mathbf{x}$	x-regressors
y	process output, output variable
w	weight
$\mathbf{z}$	z-regressors
$\mathcal{A}$	feasible set of regressors
Δ	linearised form, deviation, measurement uncertainty
ϕ	validity function
$\boldsymbol{\theta}$	parameter vector

General Physical Quantities

Symbol	Explanation	Unit
a	specific work	J/kg
A	surface area	m^2
b	width	m
C_D	orifice discharge coefficient	1
c_p	heat capacity at constant pressure	J/(kg K)
c_V	heat capacity at constant volume	J/(kg K)
c	absolute velocity	m/s
c_m	meridional part of the absolute velocity	m/s
c_u	circumferential component of the absolute velocity	m/s
d	diameter	m
h	specific enthalpy	J/kg
I	moment of inertia	kg m^2
k	heat transmission coefficient	$\mathrm{W/(m^2K)}$
l	length	m
$\dot{m}$	mass flow rate	kg/s or kg/h
m	mass	kg
M	molar mass	g/mol
M	torque	Nm
p	pressure	Pa
P	power	W
q	specific heat transfer	J/kg
$\dot{Q}$	heat flow	W
R	resistance	Ω
R	specific gas constant	J/(kg K)
t	time	s
T	temperature	K or $°C$
u	circumferential velocity	m/s
U	internal energy	J
U	voltage	V
v	velocity	km/h
V	volume	m^3
$\dot{V}$	volume flow rate	$\mathrm{m^3/s}$
w	relative velocity	m/s
w_m	meridional part of the relative velocity	m/s
w_c	circumferential part of the relative velocity	m/s
x	air content (ratio of fresh air mass to total gas mass)	1

Symbol	Explanation	Unit
α	heat transfer coefficient	$W/(m^2K)$
α	absolute flow angle, guiding vane angle	deg
β	relative flow angle, rotor blade angle	deg
δp	differential pressure	Pa or bar
κ	isentropic expansion factor	1
μ	slip factor	1
Π	pressure ratio	1
ρ	density	kg/m^3
ω	angular velocity	rad/s

Letter Symbols for Combustion Engines

Symbol	Explanation	Unit
c_{mss}	micro soot sensor measurement	mg/m^3
c_{nox}	NO_x sensor measurement	ppm
c_{opa}	opacity measurement	%
k_{af}	load factor air filter	1
k_{dpf}	load factor DPF	1
L_{st}	stoichiometric air requirement	1
m_{air}	air mass per working cycle	mg/cyc
m_{mss}	distance related particulate emissions (micro soot sensor)	mg/km
m_{nox}	distance related nitrogen oxide emissions	mg/km
m_{pm}	distance related particulate emissions	mg/km
$\dot{m}_{\mathrm{air}}$	air mass flow rate	kg/s or kg/h
$\dot{m}_{\mathrm{c}}$	compressor gas mass flow rate	kg/s or kg/h
$\dot{m}_{\mathrm{eng,in}}$	gas mass flow rate entering the cylinder	kg/s or kg/h
$\dot{m}_{\mathrm{eng,out}}$	gas mass flow rate exiting the cylinder	kg/s or kg/h
$\hat{\dot{m}}_{\mathrm{f}}$	estimated injected fuel mass flow rate	kg/s or kg/h
$\dot{m}_{\mathrm{hp-egr}}$	HP-EGR gas mass flow rate	kg/s or kg/h
$\dot{m}_{\mathrm{lp-egr}}$	LP-EGR gas mass flow rate	kg/s or kg/h
$\dot{m}_{\mathrm{mss}}$	particulate mass flow rate (micro soot sensor)	mg/s
$\dot{m}_{\mathrm{nox}}$	NO_x mass flow rate	mg/s
$\dot{m}_{\mathrm{t}}$	turbine gas mass flow rate	kg/s or kg/h
$\dot{m}_{\mathrm{th}}$	throttle valve gas mass flow rate	kg/s or kg/h
M_{c}	turbocharger compressor torque	Nm
M_{f}	turbocharger friction torque	Nm
M_{eng}	engine torque	Nm
M_{t}	turbocharger turbine torque	Nm
n_{eng}	engine rotational speed	1/min
n_{tc}	turbocharger rotational speed	1/s
op	operation point	1

Symbol	Explanation	Unit
p_1	pressure before the compressor	Pa or bar
p_{2c}	pressure after the compressor	Pa or bar
p_{2i}	pressure in the intake manifold	Pa or bar
p_{2ic}	pressure after the intercooler	Pa or bar
p_3	pressure in the exhaust manifold	Pa or bar
p_4	pressure before the particulate filter	Pa or bar
p_5	pressure after the particulate filter	Pa or bar
p_a	ambient pressure	Pa or bar
p_{hp-egr}	pressure in the HP-EGR pipe	Pa or bar
p_{lp-egr}	pressure in the LP-EGR pipe	Pa or bar
p_{rail}	pressure in the common rail injection system	bar
P_c	turbocharger compressor power	W
P_f	turbocharger friction power	W
P_t	turbocharger turbine power	W
$\dot{Q}_{i,t}$	heat transmission to state i	W
r_{egr}	EGR-rate	1
r_{lp-egr}	LP-EGR-rate	1
s_{eth}	exhaust throttle valve position (normalised)	1
s_{hp-egr}	HP-EGR-valve position (normalised)	1
s_{ith}	intake throttle valve position (normalised)	1
s_{lp-egr}	LP-EGR-valve position (normalised)	1
$s_{lp-egr/eth}$	LP-EGR-valve combined with exhaust throttle valve position	1
$s_{lp-egr/ith}$	LP-EGR-valve combined with exhaust intake valve position	1
s_{sa}	swirl actuator position (normalised)	1
s_t	VGT-actuator position (normalised)	1
s_{th}	throttle valve position (normalised)	1
$\tilde{s}_i$	Actuator position i (measured)	mm or %
T_1	temperature before the compressor	K or °C
T_{2c}	temperature after the compressor	K or °C
T_{2ic}	temperature after the intercooler	K or °C
T_{2i}	temperature in the intake manifold	K or °C
T_3	temperature in the exhaust manifold	K or °C
T_4	temperature before the particulate filter	K or °C
T_5	temperature after the particulate filter	K or °C
T_a	ambient temperature	K or °C
T_{cl}	temperature cooling fluid	K or °C
T_{h_2o}	temperature engine coolant	K or °C
T_{hp-egr}	temperature in the HP-EGR pipe	K or °C
T_{lp-egr}	temperature in the LP-EGR pipe	K or °C
u_{icc}	control signal intercooler ventilator	1
u_{inj}	desired injection quantity	mm^3/cyc

Symbol	**Explanation**	**Unit**
V_d	displacement volume	m^3
W_eng	engine work	kWh
x	air content (ratio of fresh air mass to total gas mass)	1
x_1	air content before the compressor	1
$x_{2\mathrm{c}}$	air content after the compressor	1
$x_{2\mathrm{ic}}$	air content after the intercooler	1
$x_{2\mathrm{i}}$	air content in the intake manifold	1
$x_{\mathrm{eng,in}}$	air content entering the cylinder	1
$x_{\mathrm{eng,out}}$	air content exiting the cylinder	1
x_3	air content in the exhaust manifold	1
x_4	air content before the particulate filter	1
x_5	air content after the particulate filter	1
$x_{\mathrm{hp-egr}}$	air content in the HP-EGR pipe	1
$x_{\mathrm{lp-egr}}$	air content in the LP-EGR pipe	1
z	number of cylinders per combustion cycle	1
λ	air-fuel ratio	1
λ_a	volumetric efficiency	1
φ_{mi}	start of main injection	°CA
φ_{Q50}	crank angle of 50 % mass fraction burned	°CA
$\xi_{\mathrm{hp-egr}}$	desired proportion of HP-EGR	1
$\xi_{\mathrm{p,st}}$	pipe volume fraction	1
$\chi_{\mathrm{hp-egr}}$	fraction of HP-EGR to total EGR	1
ω_{tc}	angular velocity turbocharger	rad/s

Subscripts

Index	Explanation
1	state variables before compressor
2c	state variables after compressor
2ic	state variables after intercooler
2i	state variables intake manifold
3	state variables exhaust manifold
4	state variables after turbine
5	exhaust pipe quantities
a	actuator
acc	acceleration
adi	adiabatic
af	air filter quantities
c	compressor quantities
cj	cold junction
ctl	closed-loop control
cyl	cylinder

Index	Explanation
des	desired quantity
dia	diabatic
dpf	Diesel particulate filter quantities
dyn	dynamical
eng,in	entering cylinder
eng,out	exiting cylinder
eth	exhaust throttle valve quantities
f	friction
fil	filtered
ffc	feedforward control
gas	gas
h2o	engine coolant liquid
hp-egr	HP-EGR quantities
icc	intercooler cooler
in	input, inflow
ise	isentropic
lim	limited
lp-egr	LP-EGR quantities
mair-ctl	air mass flow rate control
measured	measured
mi	main injection / mean indicated pressure
mi,lp	mean indicated pressure intake and exhaust stroke
	low pressure loop in p-V diagram
mi,hp	mean indicated pressure compression and power stroke
	high pressure loop in p-V diagram
min	minimum
mss	micro soot sensor quantities
nox	NO_x quantities
opa	opacimeter quantities
opt	optimised quantity
out	output, outflow
p	power, pipe
r	receiver
ref	reference
regr-ctl	EGR-rate control
rsf	reference shaping filtered
s	shunt
sim	simulated
stat	stationary
t	turbine quantities
tc	turbocharger quantities
th	throttle valve quantities

General Abbreviations

Abbreviations	Explanation
°CA	Unit of the Rotational Angle of the Crank Shaft
CAN	Controller Area Network
CASEM	Crank Angle Synchronous Engine Models
CLK	Clock Generator Oscillator
CO	Carbon Monoxide
cyc	Combustion Cycle
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
ECU	Electronic Control Unit
EGR	Exhaust Gas Recirculation
EMF	Electro Magnetic Fields
HC	Hydrocarbons
HCCI	Homogeneous Charge Compression Ignition
HP-EGR	High-Pressure Exhaust Gas Recirculation
IMC	Internal Model Control
LOLIMOT	Local Linear Model Tree
LOPOMOT	Local Polynomial Model Tree
LP-EGR	Low-Pressure Exhaust Gas Recirculation
LSB	Least Significant Bit
MFB50	50 % Mass Fraction Burned
MVEM	Mean Value Engine Model
NEDC	New European Driving Cycle
NO_x	Nitrogen Oxides
PM	Particulate Matter
PN	Particulate Number
PRBS	Pseudo Random Binary Signals
RDE	Real Driving Emissions
RMSE	Root-Mean-Square Error
RSF	Reference Shaping Filter
VGT	Variable Geometry Turbine
VVT	Variable Valve Timing
WLTP	Worldwide Harmonized Light-Duty Vehicles Test Procedure

Mathematical Abbreviations

Abbreviations	Explanation
$f(\cdot)$	function of $\cdot$
$f_{\text{LOLIMOT}}(\cdot)$	LOLIMOT model with the model inputs $\cdot$
$\hat{\cdot}$	modelled quantity $\cdot$
$\bar{\cdot}$	mean value of quantity $\cdot$
x	scalar
$\mathbf{x}$	vector

Abstract

Modern Diesel engines fulfil challenging requirements for emission limits, fuel consumption and ride comfort by numerous modular combinable components and mechatronical actuators. These components are utilised for precondition and aftertreatment of air, fuel and exhaust gas, which is involved in the combustion process. In this dissertation a methodology for a model-based function development with semi-physical engine models for control of air path quantities of an exemplary Diesel engine with high-pressure (HP-EGR) and low-pressure exhaust gas recirculation (LP-EGR) is developed. In this framework for function development black-box models for stationary and dynamical emission formation are utilised to optimise reference values for the air path control and to rate the developed control scheme with regard to the cumulated driving cycle emissions of the new European driving cycle (NEDC).

A combination of HP-EGR and LP-EGR represents a novel approach to significantly lower the particulate and NO_x emissions of Diesel engines. A semi-physical mean value engine model with lumped parameters is the base to analyse the system properties of the complex air path. In doing so, the additional LP-EGR shows only minor influences to the quantities charge air pressure and HP-EGR, while there are significant influences of these quantities on the LP-EGR mass flow rate. Furthermore, the LP-EGR is characterised by significant gas propagation times in the intake and exhaust system. These delays are modelled by a gas composition model, which is incorporated into the control scheme.

NO_x and particulate emissions as well as engine torque are stationary modelled by local polynomial models with input quantities of the combustion process. These quantities are air mass flow rate, charge air pressure, intake temperature and crank angle of 50 % mass fraction burned. A bilinear interpolation between engine speed and injection quantity transforms local polynomial models into global models. Models for the dynamical emission formation are given by considering the combustion as a batch process. Consequently all dynamics are included in the quantities of the cylinder charge at intake valve closing and the emission measurement dynamics. Thus, a combination of a dynamical gas composition model, stationary emission models and models for the emission measurement dynamics yield the dynamical course of the engine emissions.

The investigated system properties and the emission models deliver the control variables charge air pressure, air content and intake temperature for the engine with VGT-turbocharger, HP- and LP-EGR. A stationary optimisation with regard to emissions and engine torque delivers reference values for the air path control and further shows the potential of the LP-EGR to lower the emissions. Due to the multi-variable characteristics of the air path with different dynamics, there are increased dynamical emissions at engine transients. These dynamical emissions are lowered by dynamical optimised reference values for the air path control.

Generally, the air path is a strongly nonlinear process and the multitude of engine variants and engine operation modes result in a trade-off between achievable control quality, control robustness and number of control parameter sets. A semi-physical feedforward control, which is based upon parameterised model relationships of the mean value engine model delivers a good response to setpoint changes. Thus, the disturbance rejection can be achieved by relatively simple controllers. This results in an significantly lower application effort of control parameters and allows by its modular structure to exchange engine components without the drawback to completely re-parameterise the control parameters. A reference value transformation with modelled states of the gas composition model compensates long gas propagation times in the intake and exhaust system and delivers an optimal air content in the cylinder charge. All control concepts are validated with measurements at the engine test bench. Finally, the derived control concepts for the LP-EGR are compared to the classical HP-EGR control with regard to the cumulated driving cycle emissions. In this investigation the proportion of stationary and dynamical emissions is clearly quantified.

In a nutshell this dissertation is an important contribution for model-based optimisation and function development for the air path control of Diesel engines. The given combination of models for dynamical emission formation, dynamically optimised reference values for the air path control and semi-physical control design are a holistic framework to master the complexity and variance of future Diesel and gasoline engines.

Kurzfassung

Moderne Dieselmotoren erfüllen die hohen Anforderungen bezüglich Emissionen, Verbrauch und Fahrkomfort durch eine Vielzahl von modular kombinierbaren Bauteilen und mechatronischen Aktoren zur Vor- und Nachbehandlung der am Verbrennungsprozess beteiligten Stoffe Frischluft, Kraftstoff und Abgas. In dieser Dissertation wird am Beispielprozess eines aufgeladenen Dieselmotors mit Hoch- (HD-AGR) und Niederdruck-Abgasrückführung (ND-AGR) eine Methodik zur modularen modellbasierten Funktionsentwicklung für die Luftpfadregelung mit semi-physikalischen Modellen entwickelt. Black-Box-Modelle für die stationären und dynamischen Emissionen werden zur Optimierung der Sollwerte für die Luftpfadregelung und zur Bewertung des entwickelten Regelungskonzepts anhand der kumulierten Emssionen des neuen Europäischen Fahrzyklus (NEFZ) verwendet.

Eine Kombination von Hoch- und Niederdruck-Abgasrückführung ist ein neuer Ansatz, die Ruß- und Stickoxidemissionen von Dieselmotoren erheblich zu verringern. Ausgehend von einer semiphysikalischen Modellierung des Luft- und Abgaspfades mit konzentrierten Parametern werden die Systemeigenschaften des komplexen Luftpfades untersucht. Dabei zeigt das ND-AGR-System geringen Einfluss auf Ladedruck und HD-AGR, während selbige den ND-AGR-Massenstrom stark beeinflussen. Weiterhin kann die ND-AGR durch lange Gaslaufzeiten im Einlass- und Abgassystem charakterisiert werden. Diese Laufzeiten werden durch ein Gaszusammensetzungsmodell abgebildet und später in den Regelungsentwurf integriert.

Die Emissionen NO_x , Ruß und das Motordrehmoment werden stationär mit lokalen Polynomen mit den Eingangsgrößen Luftmasse, Ladedruck, Ladungstemperatur und Schwerpunktlage der Verbrennung modelliert. Eine bilineare Interpolation der lokalen Polynome über Motordrehzahl und Einspritzmenge liefert stationäre globale Emissionsmodelle. Betrachtet man die Verbrennung als Chargenprozess, so ergibt sich der dynamisch messbare Verlauf der Emissionen durch die dynamische Beschreibung der Zylinderfüllung beim Schließen der Einlassventile und der Messdynamik der Emissionsmessung. Durch die Kombination des Gaszusammensetzungsmodells, der stationären Emissionsmodelle und Modellen für die Messdynamik wird der dynamische Emissionsverlauf simuliert.

Aus den Systemeigenschaften und den Emissionsmodellen werden Ladedruck, Gaszusammensetzung und Einlasstemperatur als Regelgrößen für den Luftpfad mit Turbolader, HD- und ND-AGR ausgewählt. Eine stationäre Optimierung bezüglich der Emissionen und des Motordrehmoments liefert die Sollwerte für die Regelung und zeigt im Vergleich mit der HD-AGR Serienkonfiguration das Potential der ND-AGR zur Verringerung der Emissionen. Durch die unterschiedlichen Dynamiken der Regelgrößen im Luftpfad kommt es bei Arbeitspunktwechseln zu erhöhten Emissionen. Dieses Verhalten wird durch eine dynamische Optimierung der Sollwerte der Luftpfadregelung kompensiert.

Der Luftpfad ist ein stark nichtlinearer Prozess und die Vielzahl von Motorvarianten und Motorbetriebsmodi führt zu einem Zielkonflikt zwischen erreichbarer Regelgüte, Robustheit der Regelung und der dazu notwendigen Anzahl von Reglerparametersätzen. Der Einsatz einer semi-physikalischen Vorsteuerung basierend auf den parametrierten Modellgleichungen des Luftpfadmodells liefert ein sehr gutes Führungsverhalten, während das Störverhalten durch einfache Regler kompensiert werden kann. Dies verringert den Applikationsaufwand und erlaubt durch den modularen Aufbau den Austausch einzelner Motorbauteile, ohne den Nachteil einer Neuparametrierung aller Reglerkennfelder. Eine Sollwerttransformation mit modellierten Zuständen des Gaszusammensetzungsmodells kompensiert die langen Gaslaufzeiten im Einlass- und Auslasssystem des Motors und sorgt für eine optimale Gaszusammensetzung der Zylinderfüllung. Alle Regelungskonzepte werden mit Messdaten vom Motorprüfstand validiert. Abschließend werden die entwickelten Regelungskonzepte für die ND-AGR mit der klassischen Regelung einer HD-AGR anhand der kumulierten Zyklusemissionen während des NEFZ verglichen. In dieser Betrachtung wird für alle Regelungskonzepte der Anteil von dynamischen Emissionen und stationären Emissionen quantifiziert.

Zusammenfassend leistet diese Dissertation einen wichtigen Beitrag zur modellbasierten Optimierung und Funktionsentwicklung der Luftpfadregelung von Dieselmotoren. Die Kombination von dynamischen Emissionsmodellen, einer dynamischen Optimierung der Sollwerte für die Luftpfadregelung und der semi-physikalische Regelungsentwurf stellen ein ganzheitliches Vorgehen zur Beherrschung der Komplexität und Varianz von zukünftigen Diesel- und Ottomotoren dar.