Rolf Isermann

Engine Modeling and Control

Modeling and Electronic Management of Internal Combustion Engines

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Preface

The increasing requirements for automotive drives with internal combustion engines on reduced fuel consumption, low emissions and good driveability need continuous improvement of combustion and exhaust treatment processes and their control. This can be reached by a higher variability with an increase of actuators and sensors in addition to thermodynamic, mechanical and structural improvements. Modern engines have therefore an increasing number of manipulation variables and sensors and a complex electronic management. The design of the many control function requires good physical understanding and model-based methods taking into account mechatronic engineering principles.

The book treats as well physical-based as experimental gained engine models for gasoline (spark ignition) and diesel (compression ignition) engines and uses them for the design of the different control systems. The procedure and the workflow from theoretical and experimental modeling over simulations to calibration with test benches is systematically described and demonstrated by many examples. Not only the stationary but also the dynamic nonlinear behavior of engines is taken into account. The combustion engine models include the intake system, fuel supply and injection, combustion cycles, mechanical system, turbochargers, exhaust and cooling system and are mainly generated for real-time computation. Engine control structures and engine control development with different digital feedforward and feedback control methods, calibration, optimization and simulation tools are considered in detail. Various control systems are developed for gasoline and diesel engines with both, conventional and alternative combustion processes, based on nonlinear static and dynamic multivariable engine models and demonstrated by experiments on test benches.

The book is an introduction into the electronic engine management with many examples for engine control and it is oriented to advanced students working in control, electrical, mechanical and mechatronic engineering and will also be useful for practicing engineers in the field of engine and automotive engineering.

The author is grateful to his research associates, who have performed many theoretical and experimental research projects on the subject of this book since 1986, among them K.U. Voigt, Chr. Schmidt, St. Leonhardt, K. Pfeiffer, O. Nelles, Chr. Ludwig, St. Sinsel, M. Schüler, M. Willimowski, M. Hafner, O. Jost, J. Schaffnit,

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Darmstadt, May 2014 Rolf Isermann

Contents

List of Symbols

Only frequently used symbols and abbreviations are given:

1. General letter symbols

a	parameters of differential or difference equations
b	parameters of differential or difference equations
c	spring constant, constant, concentration, stiffness
d	damping coefficient
e	equation error, control deviation $e = w - y$, number $e = 2.71828\ldots$
f	fault, frequency ($f = 1/T_\mathrm{p}$, T_p period), function $f(\ldots)$
g	gravitational acceleration, function $g(\ldots)$, impulse response
i	integer, gear ratio, index, $\sqrt{-1}$ (imaginary unit)
j	integer, index
k	discrete number, discrete time $k = t/T_0 = 0, 1, 2, \ldots$ (T_0: sampling time)
l	index, length
m	mass, order number
n	rotational speed, order number, disturbance signal
p	pressure, index, controller parameter, probability density function, process parameter
q	controller parameter
r	index, radius, reference variable, residual
s	Laplace variable $s = \delta + i\omega$, symptom, actuator position
t	continuous time
u	input signal change ΔU
v	specific volume, disturbance signal
w	speed, reference value, setpoint
x	space coordinate, state variable, concentration
y	output signal change ΔY, space coordinate, control variable change ΔY, signal

z	space coordinate, disturbance variable change $\varDelta Z$, z-transform variable $z = \exp T_0 s$
$\hat{x}$	estimated or observed variable
$\tilde{x}$	estimation error
$\bar{x}$	average, steady-state value
x_0	amplitude
x_{00}	value in steady state (identification methods)
x_{d}	desired value
A	area
B	magnetic flux density
C	capacitance
D	damping ratio, diameter
E	module of elasticity, energy, potential, bulk modulus
F	filter transfer function, force
G	weight, transfer function
H	magnetic field strength, height
I	electrical current, mechanical momentum, torsion, second moment of area
J	moment of inertia, loss function
K	constant, gain
L	inductance
M	torque
N	discrete number, windings number
P	power, probability
Q	generalized force, heat
R	electrical resistance, covariance or correlation function
S	spectral density, sum, performance criterion
T	absolute temperature, time constant
T_0	sampling time
U	input variable, manipulated variable (control input), voltage
V	volume
X	space coordinate
Y	output variable, space coordinate, control variable
Z	space coordinate, disturbance variable
$\mathbf{a}$	vector
$\mathbf{A}$	matrix
$\mathbf{A}^{\mathrm{T}}$	transposed matrix
$\mathbf{I}$	identity matrix
$\boldsymbol{\theta}$	parameter vector
$\mathbf{P}$	covariance matrix
$\boldsymbol{\psi}$	data vector
α	coefficient, angle

β	coefficient, angle
γ	specific weight, correcting factor
δ	decay factor, impulse function
ϕ	correlation function, validity function
η	efficiency
ϑ	temperature
λ	thermal conductivity, forgetting factor, failure rate
μ	friction coefficient, permeability, membership function
ν	kinematic viscosity, index
π	number $\pi = 3.14159\ldots$
ρ	density
σ	standard deviation, σ^2 variance
τ	time
φ	angle
ω	angular frequency, $\omega = 2\pi/T_{\mathrm{p}}$: T_{p} period
Δ	change, deviation
θ	parameter
Π	product
Σ	sum

2. General mathematical abbreviations

$\exp(x)$	$= e^x$
$E\{\ldots\}$	expectation of a statistical variable
dim	dimension
adj	adjoint
det	determinant
Re	real part
Im	imaginary part
$\dot{Y}$	dY/dt (first derivative)
var[]	variance
cov[]	covariance
$\mathcal{F}$	Fourier transform
$\mathcal{L}$	Laplace transform
rms (...)	root of mean squared of...

3. Letter symbols for internal combustion engines

3.1 Geometry and time (DIN 1304, ISO 31)

A	area	m^2
a	acceleration	$\mathrm{m/s}^2$
b	breadth, width	m
c	absolute velocity	m/s
d	diameter	m

D	characteristic diameter	m
f	frequency	Hz
g	acceleration of free fall, gravitational acceleration	m/s^2
h	height	m
l	length	m
n	rotational speed	1/s, rpm
r	radius	m
s	actuator position	m
u	peripheral velocity	m/s
V	volume	m^3
v	specific volume	m^3/kg
w	relative velocity	m/s
ω	angular velocity	rad/s

3.2 Mechanics (DIN 1304, ISO 31)

a	specific work	J/kg
m	mass	kg
$\dot{m}$	mass flow rate	kg/s
p	pressure	Pa
C_{d}	orifice discharge coefficient	1
E	energy	J
F	force	N
J	moment of inertia	kg m^2
L	angular momentum	kg m^2/s
M	torque	Nm
P	power	W
W	work	J
$\nu, \nu = \eta/\rho$	kinematic viscosity	m^2/s
η	dynamic viscosity	Pa s
η	efficiency	1
ρ	mass density	kg/m^3
Π	pressure ratio	1

3.3 Thermodynamics and heat transfer (DIN 1304, ISO 31)

c_{p}	specific heat capacity at constant pressure	J/(kg K)
c_{v}	specific heat capacity at constant volume	J/(kg K)
Gr	Grashof number	1
H	enthalpy	J/kg
h	specific enthalpy	J/kg
L	characteristic length	m
n	polytropic exponent	1
Nu	Nusselt number	1
Pr	Prandtl number	1

Q	heat	J
$\dot{Q}$	heat flow rate	W
q	specific heat	J/kg
R	specific gas constant	J/(kg K)
Re	Reynolds number	1
S	entropy	J/K
s	specific entropy	J/(kg K)
T	thermodynamic temperature	K
U	internal energy	J
u	specific internal energy	J/kg
x	mass fraction	1
α	coefficient of heat transfer	W/(m^2 K)
κ	isentropic exponent	1
λ_{th}	thermal conductivity	W/(m K)
ϑ	temperature	K

3.4 Engine specific symbols

α_{ped}	accelerator pedal position	%
b_{f}	fuel consumption	kg/h
b_{sfc}	effective specific fuel consumption	g/kWh
c_{NOx}	nitrogen oxide concentration	g/m^3
c_{op}	opacity	%
c_{pa}	soot concentration	g/m^3
Δt_{pi}	timing of pilot injection	ms
$\Delta\varphi_{\mathrm{pi}}$	crank angle of pilot injection (difference angle to main injection)	$^\circ$CS
ϵ	compression ratio	1
h	valve lift	m
H_{l}	lower fuel heating value	J/kg
φ	crank angle	$^\circ$CS
φ_{mi}	crank angle of main injection	$^\circ$CS
φ_{ign}	ignition angle	$^\circ$CS
λ	air-fuel ratio (excess air factor)	1
λ_{a}	air expenditure	1
λ_{P}	connecting rod ratio	1
l_{r}	relative filling	1
L_{st}	stoichiometric air requirement	kg/kg
m_{f}	injection mass	mg/cyc
$\dot{m}_{\mathrm{f}}$	injection mass flow	kg/h
m_{mi}	main injection mass	mg/cyc
m_{pi}	pilot injection mass	mg/cyc
$\dot{m}_{\mathrm{eng,in}}$	gas flow into the engine	kg/h
$\dot{m}_{\mathrm{eng,out}}$	gas flow out of the engine	kg/h
m_{air}	air mass per cycle	mg/cyc

M_{aux}	auxiliaries torque	Nm
M_{cyl}	torque of one cylinder	Nm
M_{eng}	crankshaft mean torque at flywheel	Nm
M_{f}	friction torque	Nm
M_{g}	gas force torque	Nm
M_{i}	indicated torque	Nm
M_{l}	load torque	Nm
M_{m}	dynamic masses torque	Nm
M_{drg}	drag torque, motoring torque	Nm
M_{v}	valve train torque	Nm
$\dot{m}_{\mathrm{air}}$	air mass flow	kg/h
q_{f}	injection quantity	mm^3/cyc
q_{mi}	main injection quantity	mm^3/cyc
q_{pi}	pilot injection quantity	mm^3/cyc
r_{egr}	exhaust gas recirculation ratio	1
V_{c}	clearance volume per cylinder	m^3
V_{d}	displaced volume per cylinder	m^3
V_{D}	total displacement (all cylinders)	m^3
z	number of cylinders	1

3.5 Combustion pressure analysis

$dp_{\mathrm{cyl}}/d\varphi$	pressure gradient	Pa/°CS
$dQ_{\mathrm{f}}/d\varphi$	heat release rate	J/°CS
φ_{Q5}	location of mass fraction burned 5%	°CS
φ_{Q50}	location of mass fraction burned 50%	°CS
φ_{Q95}	location of mass fraction burned 95%	°CS
p_{mi}	mean indicated pressure	Pa
p_{m}	motored cylinder pressure (no injection)	Pa
p_{mep}	brake mean effective pressure	Pa
Q_{f}	heat release	J

3.6 Subscripts for internal combustion engines

1	state variables in front of the compressor
3	state variables in front of the turbine (in the exhaust manifold)
4	state variables after the turbine
5	state variables after the DPF
2c	state variables after the compressor
2i	state variables in the intake manifold
2ic	state variables after the intercooler
a	ambient
afi	air filter
afl	air flaps
air	air

b	burned
c	compressor
cam	camshaft
cas	crankshaft
cd	combustion duration
cg	combustion gas
cl	cooling medium, coolant
cool	cooling
cr	common rail
cyl	cylinder
dpf	diesel particulate filter
ds	delivery start
ec, EC	exhaust closes
eff	effective
eg	exhaust gas
egr	exhaust gas recirculation
egrc	EGR cooler
egrv	EGR valve
eng	engine
eo, EO	exhaust opens
es	exhaust system
eth	exhaust throttle valve
ev	exhaust valve
f	fuel, friction
geo	geometrical
H_2O	coolant water
hpegr	high pressure exhaust gas recirculation
hpp	high pressure pump
ic	intake closes
id	injection duration
igd	ignition delay
in	streaming in
int	intake
inj	injectors
io	intake opens
iv	intake valve
lpegr	low pressure exhaust gas recirculation
mc	main combustion
meas	measured
mi	main injection
mv	metering valve
oil	oil
osc	oscillating
out	streaming out
p	piston

pc	pilot combustion
pcv	pressure control valve
pi	pilot injection
r	rod
rail	rail system
red	reduced
rot	rotating
sim	simulated
soc	start of combustion
soi	start of injection
sw	swirl flap
t	turbine
tc	turbocharger
th	throttle
u	unburned
vac	vacuum system
vgt	variable geometry turbocharger
w	wall
wg	waste gate turbocharger

3.7 Abbreviations for internal combustion engines

AFR	air-to-fuel ratio
ASAM	Association for Standardization of Automation and Measuring Systems
BDC	bottom dead center
CI	compression ignition engine
CR	common rail
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
EGR	exhaust gas recirculation
HFM	hot film measurement
NSC	NO_x storage catalyst
OSEK	Offene Systeme und deren Schnittstellen für die Elektronik im Kraftfahrzeug (open systems and their interfaces for the electronics in vehicles)
PF	particulate filter
PM	particulate matter
SCR	selective catalytic reduction
SI	spark ignition engine
TDC	top dead center
VGT	variable geometry turbocharger
VVT	variable valve train

4. Abbreviations for identification and signal-analysis methods

ACF	Auto Correlation Function
APRBS	Amplitude-modulated PRBS
ARMA	Auto Regressive Moving Average process
CCF	Cross Correlation Function
DFT	Discrete Fourier Transform
DSFC	Square root filtering in covariance form
DSFI	Square root filtering in information form
ELS	Extended least squares
ETA	Event Tree Analysis
FDD	Fault Detection and Diagnosis
FDI	Fault Detection and Isolation
FMEA	Failure Mode and Effects Analysis
FFT	Fast Fourier Transform
FTA	Fault Tree Analysis
HA	Hazard Analysis
HCCI	Homogeneous Charge Compression Ignition
LS	Least Squares
MIMO	Multiple Input Single Output
MISO	Multiple Input Multiple Output
MLP	Multilayer Perceptron
MTBF	Mean Time Between Failures
MTTF	Mean Time To Failure = $1/\lambda$
MTTR	Mean Time To Repair
NN	Neural Net
PCA	Principal Component Analysis
PRBS	Pseudo Random Binary Signal
RBF	Radial Basis Function
RLS	Recursive Least Squares
SISO	Single Input Single Output

1

Introduction

The increasing *electronification* and *electrification* is a dominant feature of modern automotive developments. This is demonstrated by an increasing part of electrics/electronics (E/E) of the manufacturing costs from about 20 % in 1995 to 35 % in 2012. The electrics comprise primarily the electrical energy flows to the consumers through the energy board net. Frequently, former mechanical, pneumatic or hydraulic actuated components of chassis and powertrain are replaced by electrical ones. The chassis-oriented electronics serve mainly the driving behavior, safety and comfort. Powertrain electronics are used for control functions to reach good driveability, low-fuel consumption and emissions.

These developments are possible through the increasing number of *mechatronic components* in the powertrain and the chassis. Figure 1.0.1 gives some examples for engines, drive trains, suspensions, brakes and steering systems. *Mechatronic systems* are characterized by an integration of mechanics and electronics, where the integration is between the components (hardware) and the information-driven functions (software). This development has a considerable influence on the design and operation of the *powertrain* consisting of the combustion engine and the drive train. In the case of hybrid drives this includes also the electrical motor and the battery.

1.1 Historical developments

The development of sensors, actuators and electronic control for automobiles is depicted in Fig. 1.1.1. The first mechatronic products in vehicles have been anti-lock braking (ABS, 1979), electric throttle (1986), automatic traction control (TCS, 1986) and semi-active shockabsorbers (1988), followed by the electronic stability control (ESC, 1995), electric power steering (EPS, 1996), active body control (ABC, 1999) and active front steering (AFS, 2003). These large improvements served mainly for increasing safety and comfort and required many new sensors with electrical outputs, actuators with electrical inputs and micro-controller-based electronic control units. Some further steps were *driver-assistance systems* to support the driver in performing driving maneuvers. They require sensors for the surroundings and are passive

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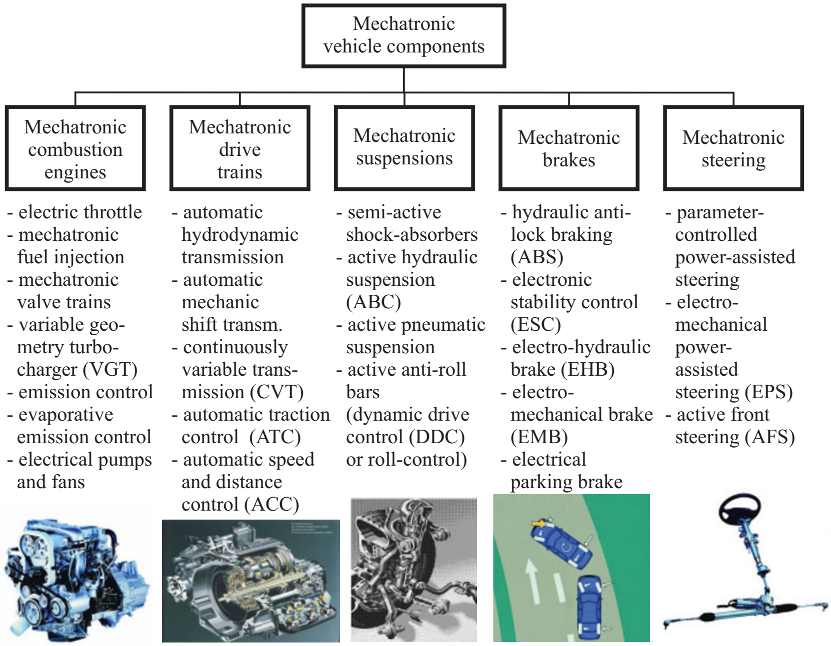

Fig. 1.0.1. Mechatronic components and systems for automobiles and engines.

by giving warnings or are active by intervening in the vehicle dynamics. Examples are parking-assistance systems which measure within the parking space and adaptive cruise control (ACC, 1999) which measures the distance and relative velocity to vehicles in front and such improve mainly the comfort and convenience of driving. Driver-assistance systems for lane-departure warning and anti-collision avoidance operate with LIDAR or RADAR and video cameras and improve primarily the safety of driving.

A common feature of these developments is the increase of electrical sensors, actuators and electronic control units, the coupling through cables and bus systems and a beginning interconnection of the decentralized control units. Some of the vehicle control systems give commands to the engine control system, as, for example, TCS, ESC and ACC.

Parallel to the increase of electronic control functions for the chassis the *engines and drive trains* have shown a similar development. This has to be seen together with the improvements of the combustion, fuel consumption and emission reductions and will be discussed in the following sections.

1.1.1 Gasoline engines (SI)

The historical development of gasoline engines during the last 50 years with view on their control is depicted in Fig. 1.1.2. Until about 1965 the engines were mechanically controlled with transistor-triggered electromechanical coil ignition. Fuel

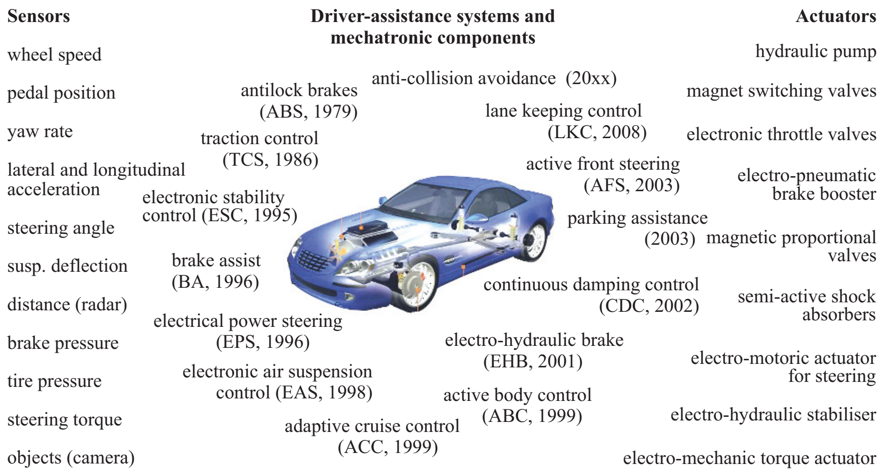

Fig. 1.1.1. Development of sensors, actuators and electronic control systems for automobiles.

injection systems for the intake manifold with electronic analog control began to replace the carburetors in 1967. Since about 1970 increasingly more functions are controlled electronically, first with transistor technology. This development required more sensors (knock sensors, air flow and air pressure sensors) with electrical outputs and actuators with electrical inputs (fuel injectors). A large influence on the developments had the state regulations and emission laws, for the United States the Clean Air Act (CARB) in California (1983) and since 1993 for US states in different tiers the laws for low emission vehicles (LEV), ultra low emission vehicles (ULEV) and super ultra low emission vehicles (SULEV). The corresponding European regulations are EURO 1 (1992), EURO 2 (1996), EURO 3 (2000), EURO 4 (2005), EURO 5 (2009), and EURO 6 (2014). These regulations were supplemented by the requirements for an on-board diagnosis in the United States OBD I (1988), OBD II (1994) etc. and EOBD (2000) for Europe.

Gasoline engines received catalytic converters with λ-control (1976) and microprocessor control in 1979. The electrical throttle was introduced in 1986, the direct injection about 1999 and since 2000 gasoline engines are supplied with variable valve trains for valve timing and lift control. Present gasoline engines are characterized by electromagnetic or piezoelectric injectors, high-pressure injection pumps (120 bar), homogeneous and stratified combustion, mechanical or turbo charging and increased specific power (downsizing). Figure 1.1.3 depicts the development of sensors and actuators for gasoline engines. Today's SI engines have about 15–25 sensors and 6–8 main manipulated variables and are controlled with a powerful microcomputer control unit (ECU) with 80–120 look-up tables and many control algorithms.

1.1.2 Diesel engines (CI)

The historical development of diesel engines with regard to their control is shown in Fig. 1.1.4. Around 1960 diesel engines had a swirl chamber, mechanically controlled

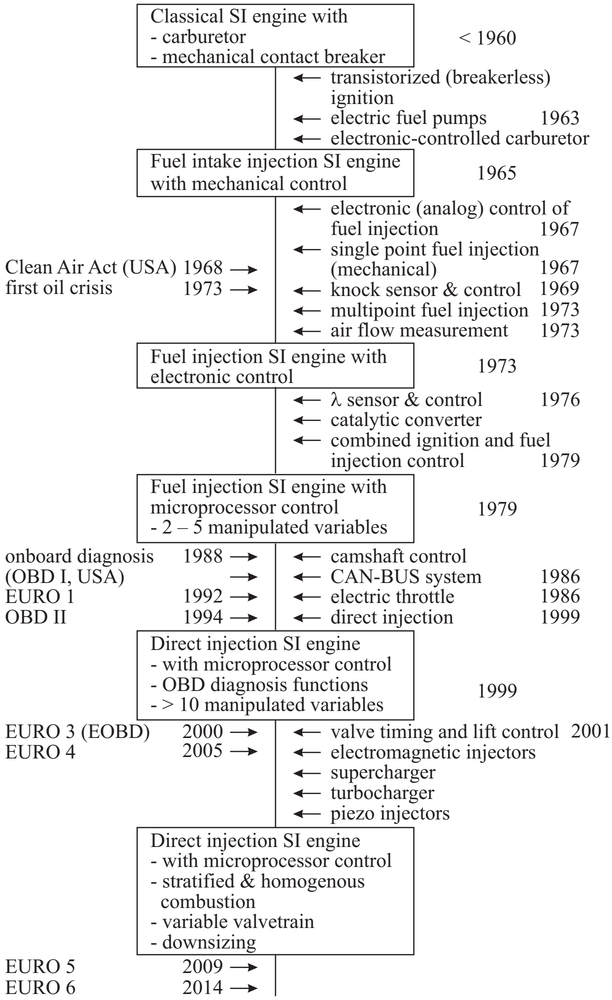

Fig. 1.1.2. Historical development of gasoline engines.

piston injection pumps and fly-weight overspeed control. Microprocessor control with direct injection and distributor pump (900 bar) and wastegate turbochargers appeared about 1989. Further steps were exhaust gas recirculation (EGR), oxidation catalyst and turbochargers with variable geometry (1992). First common-rail injection systems with direct injection (1500 bar) with VGT turbochargers reduced further fuel consumption and emissions and resulted in good dynamic torque generation. Today's diesel engines are characterized by high pressure (2000 bar), multiple common-rail injection, piezo-injectors, twin turbochargers or VGT chargers, high EGR rates, $DeNO_x$-catalyst, particulate filters with regeneration, and selective catalytic reduction (SCR).

Sensors and actuators for gasoline engines

Sensors

engine speed (1967), camshaft phase

motor temperature (1967)

manifold pressure, manifold temperature (1967)

knock sensor (1969)

air-mass flap (1973)

oxygen (lambda) (1976)

airmass hot-film (1981)

ambient pressure

throttle and pedal position (1986, E-Gas)

tank pressure

ion current

combustion pressure

source: Volkswagen AG

→ 15–25 measurements
→ 6–8 manipulation variables
→ 80–120 look-up tables

Actuators

electronic fuel injection (1967, D-Jetronic)

microelectronic-controlled ignition and injection (1979, Motronic)

electronic throttle (1986)

exhaust gas valve

secondary air valve (1994)

variable camshaft timing

direct injectors (1999)

variable geometry manifold

variable valve lift (2011)

turbocharging (2006)

Fig. 1.1.3. Sensors and actuators for gasoline engines (SI).

The development of sensors and actuators for diesel engines is summarized in Fig. 1.1.5. Present diesel engines need about 15–20 sensors, 5–9 main manipulated variables and an ECU with more than 100 look-up tables and many control algorithms.

1.2 Current engine developments

1.2.1 Gasoline engines

Current developments for the further improvement of gasoline engines are, for example, variable valve trains, downsizing and modified combustion processes.

Variable valve trains (VVT: variable valve timing) permit the improvement of the gas exchange. The conventional phase shifting of the inlet valves primarily increases the torque through early or late opening in dependence on torque and speed. In order to reduce the gas flow losses through the throttle the valves require variable timing as well as variable lift. Then the fresh air mass can be controlled by the inlet valves. In addition the residual gases can be influenced by changing the overlapping of inlet and outlet valves to improve the emissions through internal exhaust gas recirculation. Manipulation of the valve lift in two steps or continuously gives more freedom for controlling the load without throttling, see, e.g. van Basshuysen and Schäfer (2004), Braess and Seiffert (2005), Köhler and Flierl (2012). A comparison of different designs of VVT, Schulz and Kulzer (2006) shows that the fuel consumption

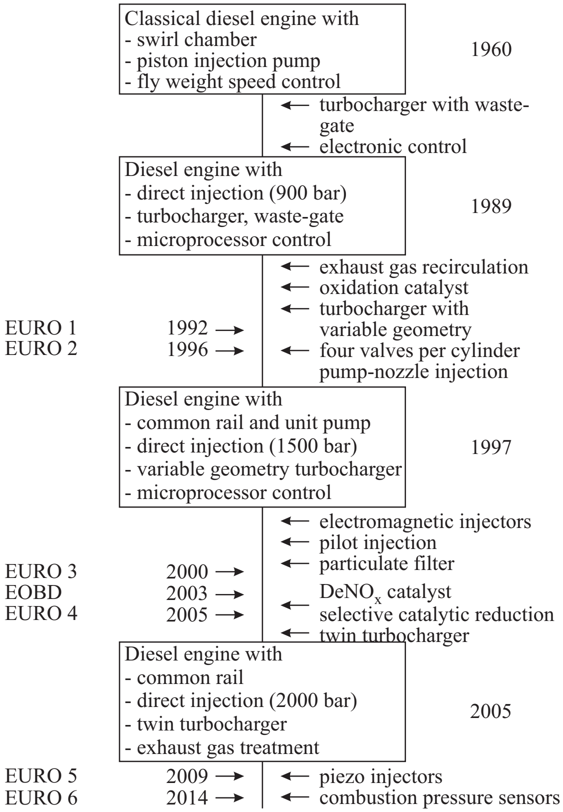

Fig. 1.1.4. Historical development of diesel engines.

can be improved with phase actuation by 3–4 %, lift switching by 8–10 %, continuously variable lift by 8–10 %, and with full variable hydraulic or electrical VVT by 14–16 %. However, the complexity is relatively high for the full variable VVT. Therefore, the first mentioned three mechanical VVT's are a good compromise.

The reduction of the displacement, i.e. *downsizing* for a given well powered vehicle leads to a smaller specific fuel consumption (less throttling) in part load, as the consumption in the torque-speed diagram shows. However, in order to increase the torque for small speeds and to reach a certain power at higher loads and speeds exhaust turbocharging or supercharging with a mechanical compressor is required. This means, for example, to reduce the displacement from 2 l to 1.3 l and an increase of the mean effective pressure from 6 to 9 bar. A comparison of different gasoline engines shows that the downsizing factor should be at least 1.3 and should be combined with a change of the operation point to higher torques by increasing the transmission ratio in the drive train (*downspeeding*) to result in a fuel reduction of about 11 %, Königstein et al (2008).

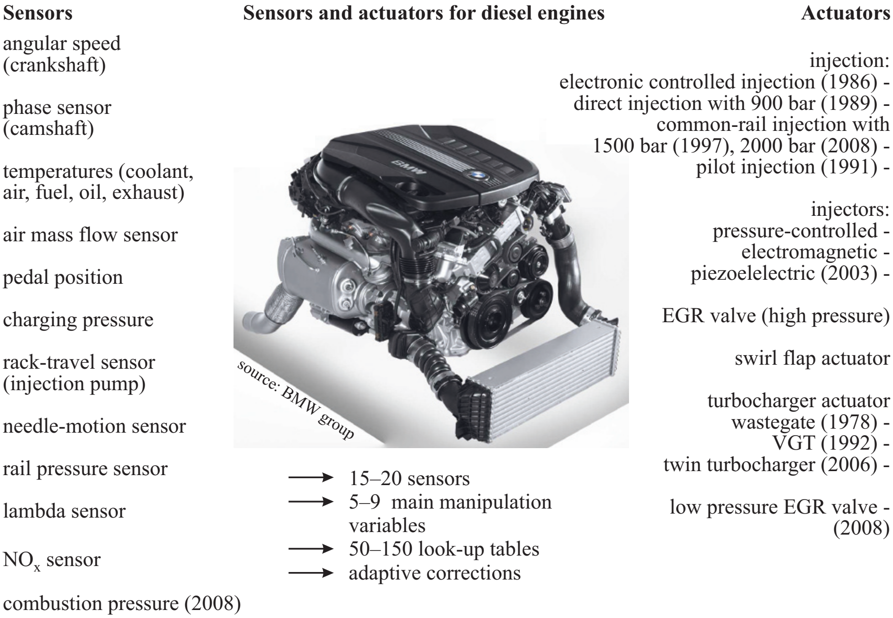

Fig. 1.1.5. Sensors and actuators for diesel engines (CI).

The optimization of the *combustion process* has of course a large influence. Compared to the conventional intake manifold injection and stoichiometric combustion with $\lambda = 1$ and three-way catalyst the direct injection into the cylinders allows considerable saving of fuel consumption for SI engines. Together with a VVT a reduction of 10 % is possible. High-pressure injectors (120 bar) with piezoelectric actuation gives a better spraying and makes a stratified, lean combustion with $\lambda > 1$ in part load possible, resulting in about 15 % fuel saving, Weingärtner et al (2007), Berns (2007). A homogeneous charge compression ignition (HCCI) with an increase of the gas temperature by increased residual gases can be obtained, for example, through early closing of the outlet valve and early injection. The combination of early closing the outlet valve and late opening of the inlet valve enables a recompression and a first injection, which can be applied for part load up to 40 %, Alt et al (2008), Backhaus (2008). However, this requires a combustion pressure measurement and control and full variable VVT. A reduction of fuel consumption of about 13–19 % is expected and a NO_x-catalyst becomes unnecessary.

1.2.2 Diesel engines

Of current interest for the further development of diesel engines are a reduction of fuel consumption, NO_x and particulates. This can be reached by further improvements of the common-rail direct injection, combustion processes, charging and exhaust-gas treatment.

Some steps for the *common-rail direct injection* are higher pressures (2200 bar) and multiple injections in order to improve the combustion, emissions and noise. Solenoid and fast piezoelectric injectors allow different combinations of pre-, main- and post-injection pulses. An increase of the exhaust-gas recirculation rate with strong cooling results in low NO_x emissions. However, a too strong increase of the EGR reduces the turbocharger power. Therefore a low-pressure EGR after the particulate filter through a cooler to the compressor inlet can be added. Then high EGR rates with a good mixture of fresh air and exhaust-gas and low temperature through an intercooler may lead to a good cylinder filling, Berns et al (2004), Hadler et al (2008). This requires several catalysts and regeneration phases and more sensors in the exhaust path, Bauer et al (2007).

A *modification of the combustion process* is the homogeneous compression ignition (HCCI), which can, e.g. be realized by an early injection with a high EGR rate in the part-load area. This leads to a strong reduction of NO_x and particulates. However, it needs a combustion feedback control with combustion pressure measurement because of the narrow possible operation limits and concentration differences in the individual cylinders, see e.g. Alt et al (2008), Backhaus (2008).

The use of *two turbochargers* with a small and large diameter enables an operation with better efficiencies, a high medium charging pressure over a larger speed range and results in improved acceleration at low speeds. The turbochargers are switched with pneumatic flaps, Steinparzer et al (2007). Also diesel engines allow a certain downsizing by increasing the specific power.

Especially large efforts go into the *exhaust treatment*, for example, through oxidation catalyst converters and particulate filters for minimization of CO, HC, NO_x and particulates. An alternative is the selective catalytic reduction (SCR) with the injection of dissolved urea, especially for heavy duty vehicles. The combination of oxidation catalyst, particulate filter, NO_x-storage catalyst and H_2S-catalyst results in a reduction of NO_x by 90 % without additives, however requires model based control and several additional sensors, and three different regeneration cycles, Hadler et al (2008).

Summarizing, *gasoline and diesel engines* show several development lines, to improve the torque generation and to decrease fuel consumption, emissions and noise. Their present development can be characterized by:

- reduction of fuel consumption and CO_2 emissions
- reduction of specific emissions (HC, CO, NO_x, particulates, dust)
- powerful exhaust gas after-treatment systems
- good driving behavior
- increased specific power (downsizing, charging)
- reduction of friction
- auxiliaries: minimization of energy consumption
- reduction of oscillations and noise.

With regard to the increasing variabilities and control functions the engines are supplied with *mechatronic components*. Figure 1.2.1 depicts some of these components.

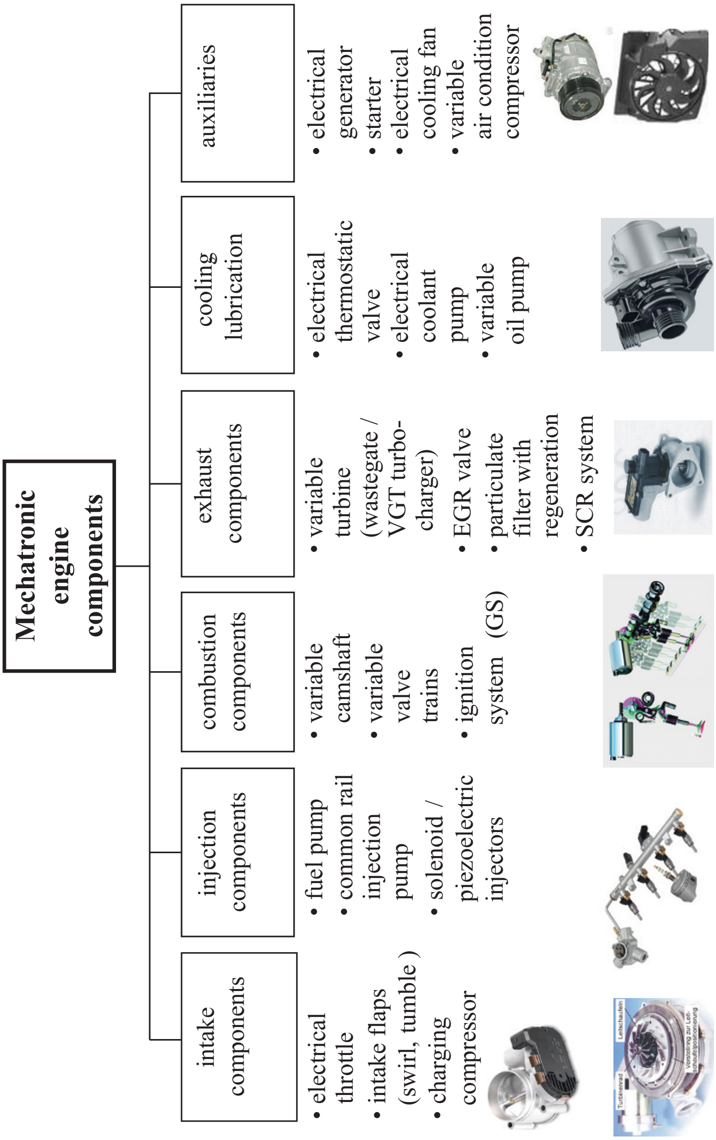

Fig. 1.2.1. Mechatronic components of internal combustion engines.