AUTOMOTIVE CONTROL SYSTEMS

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Contents

Summary

Automotive Control Systems are an application area of Automatic Control Science with increasing importance. A generation ago, vehicles were mainly designed by mechanical engineers. Today, about 1/3 of a vehicle's added value is electronics. Customer-relevant vehicle functions are more and more determined by information and automation technology. The basic ideas of system dynamics, feed-back, and signal processing are vital for the development process. In the following section, a few examples for Automotive Control Systems are presented.

1. Introduction

Automatic control becomes more and more important for the automobile industry. In application areas such as passenger safety, environmental protection and passenger comfort, control functions are implemented in the vehicle electronic control units. In the engine control unit for example, there are several algorithms to reduce emissions, to improve the engine power output and to protect against damage from engine failures.

Compensation of drivetrain oscillations and the adaptive control of automatic gear boxes are examples for applications in the drivetrain area. ABS control, suspension control and vehicle dynamic control increase the driveability of the vehicle and support the driver in dangerous situations. Airbag-systems with automatic recognition of seat occupancy improve passive safety of the passengers in case of an accident. Another large area of control applications are comfort functions like air-condition or navigation systems.

Most of these functions require sophisticated signal processing and control algorithms, which are based on models for the system dynamics. In this chapter it is impossible to present all the systems already available today. Therefore some of the most important models and controller designs are discussed, such as lambda, idle-speed and knock control in the engine and vehicle modeling and ABS braking in vehicle dynamics. In bibliography several books are listed with more detailed information about controller design in automotive applications.

2. Potential of Alternate Fuels and Propulsion Systems

Internal combustion engines are mostly employed in today's vehicles. In order to understand this, alternative fuels and propulsion systems are investigated. In Figure 1, the relative energy requirements to move a vehicle by 100km are shown for different propulsion systems.

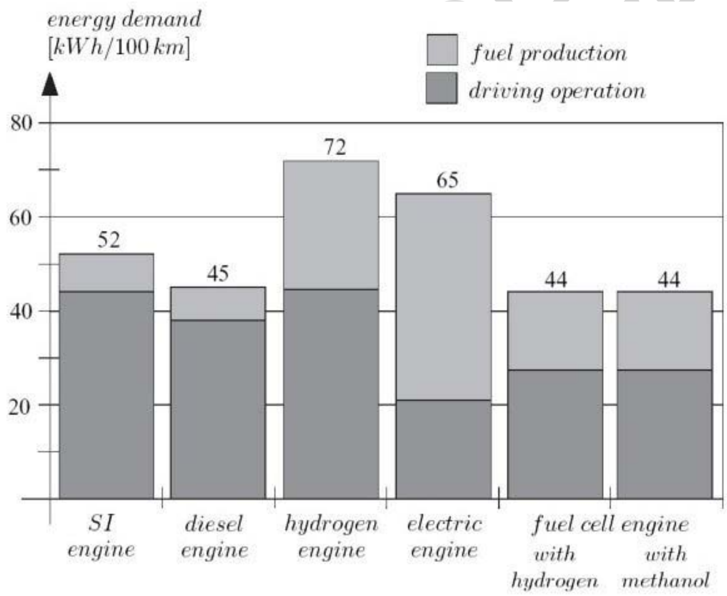

Figure 1: Relative Energy demand of different engine concepts

Electrical drives are available for more than a hundred years. The problem is the energy/fuel storage. Standard *lead batteries* are much too heavy for energy storage. Other types of batteries are lighter, but they are still not comparable to the weight of ordinary fuel. Power is dissipated in the charging and discharging processes of the battery, reducing the overall efficiency.

Eventually, battery driven vehicles with a reduced buffer size may be used in special applications at short distances. Another promising approach is that of hybrid vehicles, where an internal combustion engine is combined with an electrical motor. The electrical motor may be activated to smooth out transients of the combustion engine and the driveline, contributing to reduced noxious emissions. Under partial load conditions the combustion engine can also charge the battery, so that battery volume and weight are significantly reduced.

Hydrogen (H_2) gas is too voluminous to be directly used as an adequate energy source. It can be stored either at an extremely cold temperature of 20° K or at relatively high pressure at room temperature. Over long time periods, H_2 leaks through even thick walled steel tanks. In hydride buffers, H_2 is chemically bound. Since hydrogen burns at high combustion temperatures, emissions of nitrogen oxide (NO_x) become a problem.

Fuel cells produce electrical energy directly at low temperatures. Thermal efficiencies of 70% are reached for the synthesis of H_2 and O_2. The storage of hydrogen is again the problem. If H_2 must be therefore generated from natural gas or from methanol, efficiencies become much lower. The task is to generate the exact amount of hydrogen from, for instance methanol, even under realtime transient drive conditions. For this the fuel conversion process can be modeled, and the actual masses reacting in the conversion process be estimated in realtime, as a basis for state space control. *Fuel cells* appear to be a promising alternative to combustion engines.

Table1 illustrates that the weight and volume of stored fuel vary a lot. It can be understood, why gasoline or diesel fuels are dominating today's propulsion systems.

Source	Volume V in [l]	Mass m_1 in [kg]	Tank m_2 in [kg]	Mass+Tank $m_1 + m_2$ in [kg]
Fuel	117	83	21	104
Diesel	102	85	17	102
Methanol	224	180	41	221
Liquid gas	153	78	90	168
Methane	259	72	500	570
H_2, liquid	426	30	142	172
H_2, hydride buffer	200	30	970	1000
Battery (lead)	5000	0	10000	10000

Table 1: Weight and volume of stored fuel with an energy of 1000 kWh

3. Basic Engine Operation

Four-stroke engines are characterized by two alternate cycles: In the first cycle, equivalent to the first and second piston strokes, the gas is compressed, combusted and expanded. In the second cycle, equivalent to the third and fourth piston strokes, the gas is transferred to the exhaust pipe and the cylinder is filled with fresh air from the intake manifold. Figure 2 shows the in-cylinder pressure over the combustion chamber volume for the two cycles. The crankshaft is turned 360° per cycle.

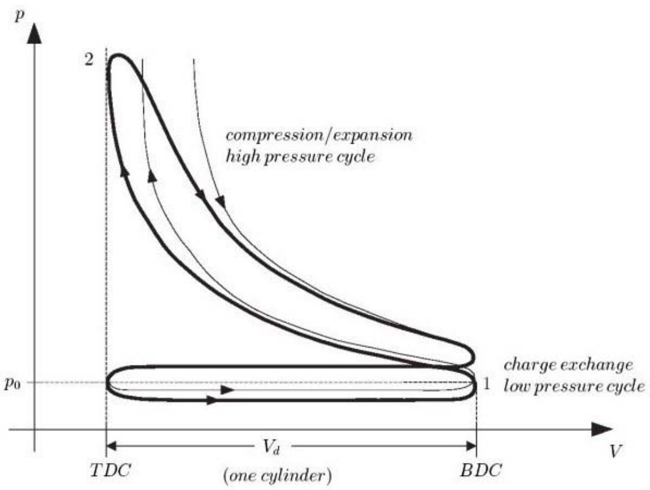

Figure 2: In-cylinder pressure over combustion chamber volume

SI and diesel engines are controlled differently: In diesel engines, the amount of injected fuel per combustion stroke is controlled proportional to the desired engine torque. Diesel engines always operate with a lean mixture, i.e. much more air than required to burn the fuel. Combustion is caused by self-inflammation due to the high compression.

In spark ignition (SI) engines, fuel as well as air flow are controlled. SI engines operate with a homogenous stoichiometric mixture at high engine loads, i.e. the air-fuel ratio lambda is suited for an almost ideal combustion. At low engine loads, direct-injected SI engines operate with lean mixtures. Combustion is triggered by the ignition spark. The mechanical work generated in the combustion cycle can be obtained by integration in the pV-diagram. The mechanical work can be normalized when relating it to the displacement volume V_d:

$$w_i = \frac{1}{V_d} \sum_{j=1}^{CYL} \oint (p_j(V_j) - p_0) dV_j \qquad (1)$$

where:

$V_d = CYL \cdot (V_1 - V_2)$ is the displacement volume of all cylinders
CYL is the number of cylinders
w_i is the (normalized) **indicated specific work**.

The value of w_i can be determined by measuring the in-cylinder pressure during a cycle. An indicated specific work of 1J/cm^3 is equivalent to a mean pressure of $\overline{p} = 10\,\text{bar}(=10^6\text{ Pa})$.

The indicated thermodynamic efficiency (friction not considered) is:

$$\eta_i = \frac{w_i}{2m_f H_f} \cdot \frac{V_d}{CYL} \tag{2}$$

where:

m_f is the mass of fuel measured per combustion stroke in kg

H_f is the specific energy of the fuel released in the combustion J/kg

(V_d / CYL) is displacement volume per cylinder

4. Lambda Control

At the stoichiometric operation of SI engines, emission levels heavily depend on how accurately the air-fuel ratio can be kept at $\lambda = 1$. Due to measurement and computational tolerances, sufficiently accurate stoichiometric operation requires a closed-loop control of the air-fuel ratio λ.

Figure 3 shows the emissions at different air-fuel ratios. For $\lambda = 1$, the raw emissions of HC, CO and NO_x before catalytic converter should be zero under ideal conditions. Due to turbulence and local inhomogeneity of the gas mixture, the actual combustion still produces HC, CO and NO_x simultaneously. By means of a catalytic converter, these raw emissions can be effectively reduced. A lambda sensor is mounted into the exhaust pipe. This sensor has a highly nonlinear characteristic.

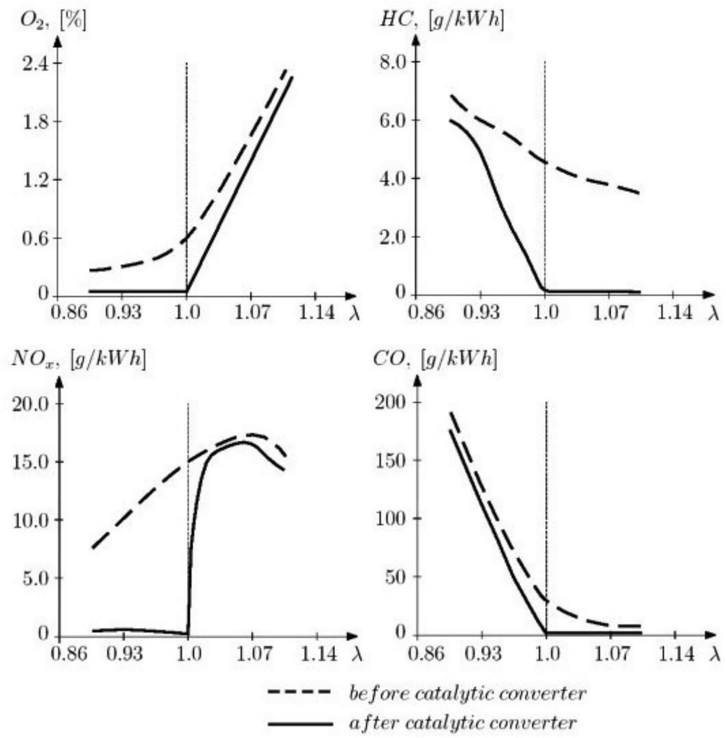

Figure3: Emission at different air-fuel ratios

The closed loop-control circuit comprises a non-linear element $N(\Delta\lambda_g)$ and a time delay $T_{d,e}$ (Fig. 4). Therefore it performs a limit cycle. For an analytic calculation the method of the harmonic balance is used. The input of the nonlinear element receives a sine function with the amplitude of the limit cycle $\Delta\lambda_g$. The first coefficient of a Fourier expansion yields the amplitude of the output signal.

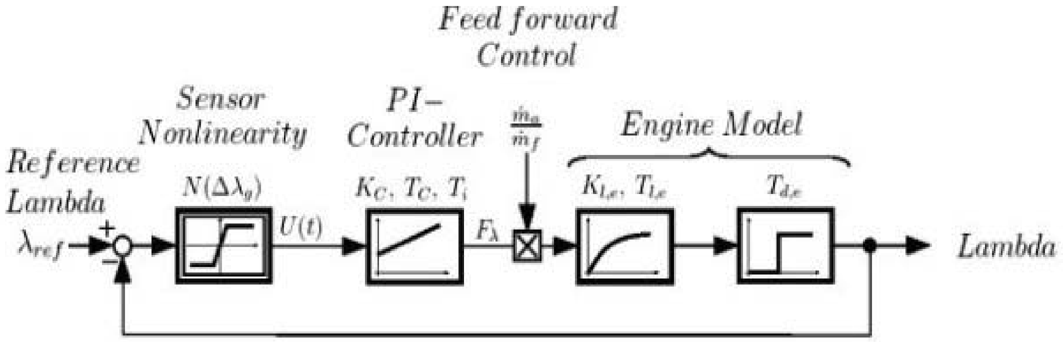

Figure 4: Closed loop control circuit of lambda control

First, the time parameter T_C of the PI controller is chosen to compensate the time delay $T_{l,e}$ of the engine:

$$T_C \approx T_{l,e} \qquad (3)$$

The frequency of the limit cycle ω_g is then:

$$\omega_g = \frac{\pi}{2 \cdot T_{d,e}} \qquad (4)$$

The integration time constant T_i of the PI controller depends on the engine dead time $T_{d,e}$.

$$T_i > \frac{8}{\pi^2} \cdot \frac{\Delta\lambda_L}{\Delta\lambda_g} \cdot \frac{K_L}{K_C} \cdot T_{d,e} \qquad (5)$$

The dependence of the parameter $T_{d,e}$ on the operating point of the engine requires a controlled adaptation of the parameter T_i. The maximum amplitude of the limit cycle is constrained by the lambda-window to (Fig. 3):

$$\frac{\Delta\lambda_g}{\lambda} \leq 3\% \qquad (6)$$

The emissions before and after the catalytic converter of a lambda-controlled engine can be seen in Fig. 5.

Due to nonlinearities and the time delay in the control loop, a limit cycle is also found for other controllers. A significant improvement can be achieved by means of an additional adaptive feed-forward control map. In every operating point of the engine, a lambda mismatch leads to modified parameters in the map.

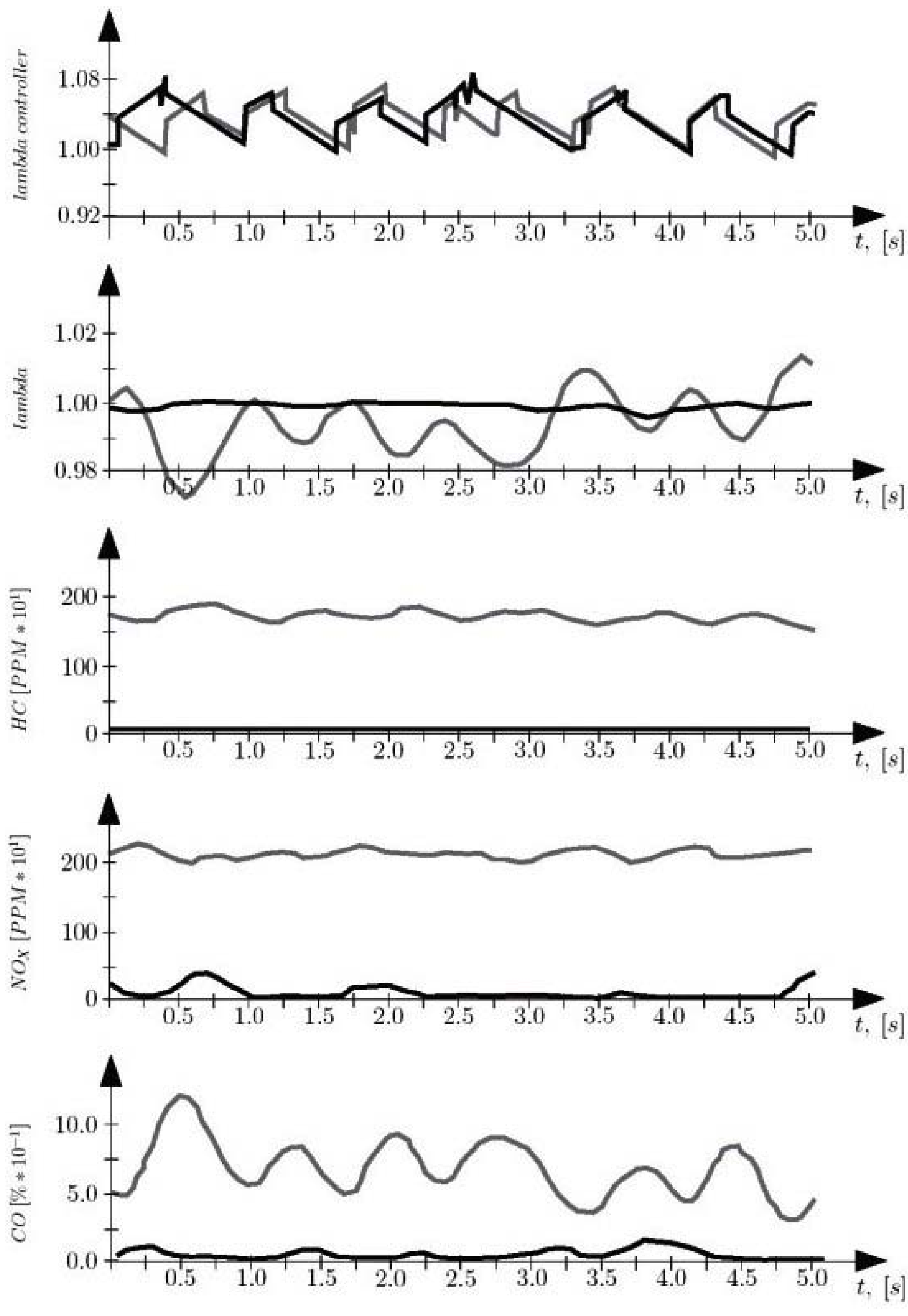

Figure 5: Emissions before and after catalytic converter

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Biographical Sketch

Uwe Kiencke was born on May the 5th, 1943. In 1967 he received his Engineering Diploma at the University of Karlsruhe (TH) in electrical engineering. Thereafter he was working on his PhD thesis at the University of Braunschweig in the area of "Inkrementrechenschaltungen zur Interpolation bei einem Sichtgerät" until 1972.

Between 1972 and 1981 Uwe Kiencke was working at Robert Bosch GmbH, Germany, in various engine management and vehicle control areas. From 1981 until 1987 he was Department Manager in Advanced Systems Development at Robert Bosch GmbH. In this period he was responsible for many research areas. One of the most important was the development of the CAN-Bus. Between 1988 and 1992 Uwe Kiencke was Group Director of Research and Development at Siemens Automotive, Germany.
Since 1992 Uwe Kiencke is Professor of Electrical Engineering at the University of Karlsruhe (TH) and head of the Institute of Industrial Information Technology. His fields of research and teaching are Automotive Control Systems, Distributed Realtime Systems and Signal Processing. In this position Uwe Kiencke was also coordinating the OSEK/VDX standard. Furthermore he is chairman of the IFAC Coordinating Committee for Transportation and Vehicles.