

Diagnosis of gasoline engines

The model-based approach for the fault diagnosis of gasoline engines follows a modular structure. The engine is divided in engine parts and their components, actuators, standard sensors and additional sensors. Following fault-detection modules are defined, compare Tables 3.3.2 and 3.3.3:

- A1 Intake system
- A2 Fuel injection system
- A3 Fuel supply
- A4 Combustion system and mechanics
- A5 Lubrication system
- A6 Exhaust gas system, emission aftertreatment
- A7 Cooling system
- B1 Electrical system
- B2 Ignition system
- C3 Electronic control.

The following sections describe a selection of advanced fault-detection and diagnosis methods. These methods have to be considered in addition to the established OBD functions, sketched in Sect. 3.2. As well signal-model as process-model-based fault-detection methods are developed. The process models used for model-based fault detection are based on physical laws or on experimental models, or on both, called semi-physical models.

4.1 Intake system (air path manifold)

4.1.1 Fault diagnosis of the intake system with physical models

In the following, the detection of sensor faults, leakage and clogging in the intake system is considered.

Air charge determination

As the air charge into the cylinders \dot{m}_{air} cannot be measured directly it has to be reconstructed based on the measurements of other variables, like air flow rate \dot{m}_1 before the throttle, manifold pressure p_2 or throttle position α_{th} , see also Müller (2003a), Guzzella and Onder (2004), Isermann (2014).

Air flow measurement

The most direct method is to measure the air flow rate \dot{m}_1 before the throttle and after the air filter, e.g. by a hot-film sensor HFM. In contrast to other flow meters, the HFM sensor directly measures the mass flow rate, possesses a wide measurement range of 1 : 50 and has a small time constant. In stationary condition it holds for the air flow rate into the cylinders

$$\dot{m}_{2,\text{air}}(t) = \dot{m}_{\text{HFM}}(t) = \dot{m}_1(t) \quad (4.1.1)$$

if no gases enter the manifold, i.e. for $\dot{m}_{\text{add}} = 0$. In dynamic operation, however, $\dot{m}_{2,\text{air}}$ into the cylinders is delayed by the intake manifold pressure dynamics. This can be taken into account by, Isermann (2014)

$$^1 \tilde{\dot{m}}_{2,\text{air}}(t) = \dot{m}_1(t) - \frac{V_{\text{int}}}{RT_2} \frac{dp_2(t)}{dt}, \quad (4.1.2)$$

where V_{int} is the intake volume. Correcting the measured air flow rate by the first derivative of the manipulated pressure allows to determine the air charge in dynamic operation. Because of the included noise and periodicity in $p_2(t)$ this signal has to be low-pass-filtered before the derivation, see Schwarte et al (2002). Further required measurements are p_2, T_2 . If additional gases \dot{m}_{add} enter the manifold intake, the manifold pressure p_2 does not only depend on $\dot{m}_{\text{air},\text{in}}$ but also on \dot{m}_{add} , see Isermann (2014). Then, $p_2(t)$ and dp_2/dt changes. However, the dynamic correction of (4.1.2) is approximately applicable, if e.g. \dot{m}_{egr} is not very large compared to $\dot{m}_1(t)$.

Manifold pressure measurement

In order to save the air flow sensor, the charge air can be determined by the manifold pressure p_2 . The gas flow rate $\dot{m}_{\text{gas,cyl}}$ into the cylinders follows, taking the additional gases with flow rate \dot{m}_{add} into account

$$^2 \tilde{\dot{m}}_{2,\text{air}}(t) = \frac{\eta_v(n, \rho_2)}{2RT_2} V_D n p_2(t) - \dot{m}_{\text{add}}(t). \quad (4.1.3)$$

As the sucked gas directly depends on the dynamically measured $p_2(t)$ the dynamics of the intake manifold are already included. This air charge determination needs the measurement of p_2 and T_2 , the calibrated volumetric efficiency $\eta_v(n, \rho_2)$, due to (5.1.2) and determination of \dot{m}_{add} .

Measurement of throttle position

Another possibility to circumvent an air flow sensor is to base the air charge determination on the known throttle angle α_{th} . Then, the flow equation of a throttle can be used

$${}^3\tilde{m}_{2,\text{air}}(t) = c_{\text{th}}(\alpha_{\text{th}}, n) A(\alpha_{\text{th}}) p_{\text{a}} \sqrt{\frac{2}{RT_{\text{a}}}} \Psi\left(\frac{p_2(t)}{p_{\text{a}}}\right) - \frac{V_{\text{int}}}{RT_2} \frac{dp_2(t)}{dt}, \quad (4.1.4)$$

where $A(\alpha_{\text{th}})$ is the effective cross section. This method requires measurement of α_{th} , p_{a} , T_{a} , p_2 , T_2 and calibration of the loss factor $c_{\text{th}}(\alpha_{\text{th}}, n)$. The final air charge mass for one cylinder follows according to

$$m_{\text{air},\text{cyl}} = \tilde{m}_{2,\text{air}} \frac{2}{i_{\text{c}} n}. \quad (4.1.5)$$

Table 4.1.1 shows a comparison for the required sensors of the three methods. In all cases p_2 , T_2 are required. Using the manifold pressure p_2 is dynamically fast but requires precise calibration of the volumetric efficiency and determination of additional gas flows \dot{m}_{add} . The application of the throttle angle needs also ambient pressure p_{a} and temperature T_{a} and precise calibration of the throttle loss factor c_{th} . The required measurements for stationary operating conditions only are summarized in Table 4.1.2. Because the dynamic compensation is then not needed, p_2 or T_2 must not be measured for some cases.

A comparison of the three ways of air flow determination was made by Müller (2003a). Most suited is the direct air flow measurement with dynamic compensation. The accuracy of the other methods depends much on a precise calibration of the correction factors. Average deviations of about 2.5% could be reached.

Table 4.1.1. Methods for the determination of the air flow rate into the cylinders with different sensors and dynamic compensation of the intake manifold delay.

Basic sensor		Additional sensors						Calibration of
		p_{a}	T_{a}	p_2	T_2	n	\dot{m}_{add}	
air mass flow	\dot{m}_1	-	-	✓	✓	-	✓	V_{int}
manifold pressure	p_2	-	-	-	✓	✓	✓	η_v
throttle angle $p_2/p_{\text{a}} \geq 0.528$	α_{th}	✓	✓	✓	✓	✓	-	$c_{\text{th}}, V_{\text{int}}$
throttle angle $p_2/p_{\text{a}} < 0.528$	α_{th}	✓	✓	-	✓	✓	-	$c_{\text{th}}, V_{\text{int}}$

Sensor faults

If the intake manifold is equipped with sensors for air flow rate, pressure, temperature and throttle angle, then there exists some analytical redundancy. The three methods for air flow determination treated in Isermann (2014) can be used to formulate output residuals of parity equations. This becomes straight forward for the case of stationary behavior, $\dot{m}_{\text{egr}} = 0$, overcritical p_2/p_{a} and negligible other mass flows \dot{m}_{add} , since then different sensors are used. Three residuals can be determined:

$$r_{\text{mair1}} = \dot{m}_1 - {}^1\tilde{m}_{2,\text{air}}(p_2, T_2) \quad (4.1.6)$$

$$r_{\text{mair2}} = {}^2\tilde{m}_{2,\text{air}}(p_2, T_2) - {}^3\tilde{m}_{2,\text{air}}(p_{\text{a}}, T_{\text{a}})_{\text{overcrit.}} \quad (4.1.7)$$

$$r_{\text{mair3}} = \dot{m}_1 - {}^3\tilde{m}_{2,\text{air}}(p_{\text{a}}, T_{\text{a}})_{\text{overcrit.}} \quad (4.1.8)$$

Table 4.1.2. Methods for determination of the air flow-rate into the cylinders for stationary operation.

Basic sensor		Additional sensors							Calibration
		p_a	T_a	p_2	T_2	n	\dot{m}_{add}	of	
air mass flow	\dot{m}_1	-	-	-	-	-	✓	-	
manifold pressure	p_2	-	-	-	✓	✓	✓	η_v	
throttle angle $p_2/p_a \geq 0.528$	α_{th}	✓	✓	✓	-	✓	-	c_{th}	
throttle angle $p_2/p_a < 0.528$	α_{th}	✓	✓	-	-	✓	-	c_{th}	

The used measurements are depicted in Fig. 4.1.1. These residuals are becoming symptoms of the air system (resp. intake system) S_{int1} , S_{int2} , S_{int3} if they exceed certain thresholds and are valid for the respective engine operating point. Table 4.1.3 lists the resulting changes of these symptoms for offset faults of six sensors. The resulting patterns are different and therefore the faults are isolable. However, if one of the three basic sensors \dot{m}_1 , p_2 and α_{th} for air flow determination is missing, only one residual can be calculated and a unique determination of the faulty sensor is not possible.

Table 4.1.3. Expected fault-symptom table for *positive offset sensor faults*, stationary engine operation, overcritical flow through throttle, $\dot{m}_{egr} = 0$ and no additional gas flows $\dot{m}_{add} = 0$.

Sensor faults		Symptoms		
		S_{int1}	S_{int2}	S_{int3}
		r_{mair1}	r_{mair2}	r_{mair3}
air mass flow	$\Delta \dot{m}_1$	+	0	+
manifold pressure	Δp_2	-	+	0
manifold temperature	ΔT_2	-	-	0
ambient pressure	Δp_a	0	+	0
ambient temperature	ΔT_a	0	-	+
throttle angle	$\Delta \alpha_{th}$	0	-	-

Leakages and clogging

As *leaks* are additive faults to the gas flows the parity equations (4.1.6) to (4.1.8) can be used, as for offset sensor faults. Table 4.1.4 shows the resulting symptoms.

The residual r_{mair3} expresses differences between the measured air flow and the calculated air flow through the throttle. Its increase indicates a leak between the air flow sensor and the throttle. A leak between the throttle and the cylinder input increases p_2 and reduces \dot{m}_1 . Therefore, residuals r_{air1} and r_{air3} become negative. (A residual for the manifold pressure can also be formed. However, its information is included in r_{air2} as it depends directly on p_2 due to (4.1.3)).

A further symptom for leakage can be obtained from the λ -controller output. Additional air flow with regard to the measured \dot{m}_1 , which determines the injected

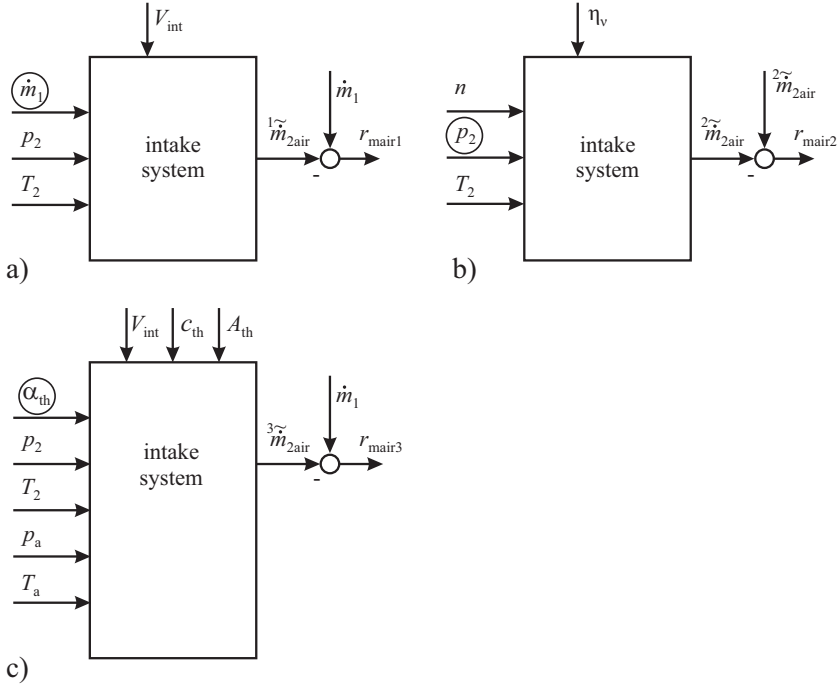


Fig. 4.1.1. Used measurements for the fault detection of the intake system with parity equations by using the air mass flow rate. Basic measurements are: **a** mass flow rate. **b** manifold pressure. **c** throttle position.

fuel mass, leads to a larger correcting factor $c_\lambda > 1$ within the ECU. Therefore, the residual

$$r_{exh1} = r_\lambda = c_\lambda - 1.0 \quad (4.1.9)$$

is an indication for a leakage after the air flow measurement, leading to symptom S_{exh1} .

Partial *clogging* or pollution with deposits is typical for the air filter in front of the throttle, at the throttle cross sectional area, in the manifold after the exhaust gas recirculation connection and at swirl or tumble flaps. The main effect is generally an increase of flow resistance which shows up in a change of the manifold pressure and/or gas flow and reduces the volumetric efficiency. For a clogged air filter the residual r_{mair2} and r_{mair3} decrease because of the decreased pressure before the throttle and for clogging within the manifold r_{mair2} decreases because of reduced volumetric efficiency η_v .

The resulting patterns for the symptoms S_{int2} and S_{int3} in Table 4.1.4 are different and therefore the leakages and the location of clogging can be diagnosed. A comparison with Table 4.1.3 shows, that for positive and negative sensor offsets the patterns of the symptoms S_{int1} , S_{int2} and S_{int3} (with one exception) are different and therefore isolable. The overcritical pressure ratio over the throttle was assumed, be-

cause then the air flow equation for the throttle (4.1.4) is less dependent on calibrated parameters.

Summarizing, the measurement of the signals shown in Fig. 4.1.1 allow to detect and isolate sensor faults, leakages and partial clogging. However, this is no more possible if one of the sensors air flow, throttle angle and manifold pressure is missing.

Table 4.1.4. Expected fault-symptom table for the intake system with *physical models* of the air mass flow for leaks and clogging with overcritical flow through throttle and no additional gas flows, $\dot{m}_{\text{add}} = 0$.

Faults	Symptoms and residuals			
	$S_{\text{int}1}$	$S_{\text{int}2}$	$S_{\text{int}3}$	$S_{\text{exh}1}$
	$r_{\text{mair}1}$	$r_{\text{mair}2}$	$r_{\text{mair}3}$	r_{λ}
leakage before throttle	—	0	—	0
leakage after throttle	—	+	—	+
clogging of air filter	—	0	0	0
clogging within manifold	—	—	0	0

4.1.2 Fault diagnosis of the intake system with experimentally identified models

a) Case 1: fuel stratified direct injection gasoline engine

As treated in the last section the physically based models for the behavior of the intake manifold system require several experimentally determined parameters, correcting factors in the form of at least two dimensional look-up tables. An alternative is then to apply directly nonlinear models which are developed by identification methods. This was investigated by Hartmanshenn and Isermann (2005) and Leykauf and Isermann (2008).

A direct-injection gasoline engine VW FSI 1.6 l (max. power 81 kW, max. torque 155 Nm) on a dynamic test rig was used for the experimental investigations. The engine combustion changes, after the warm-up phase depending on the engine load, between different operating modes: homogeneous ($\lambda = 1$), stratified-homogeneous ($\lambda = 1.5$) and stratified mode ($\lambda > 1$). Figure 4.1.2 depicts the standard and some additional sensors of the investigated engine. A scheme of the modular structure for the diagnosis system is presented in Fig. 4.1.3.

Modeling with local linear net models

The intake system is experimentally modeled with local linear net models and a multiple-input single-output (MISO) structure. The used output signals for the intake system are air flow \dot{m}_{air} and manifold pressure p_2 with the input signals shown in Fig. 4.1.4. The identification and parameter estimation was performed with the LOLIMOT method, Hartmanshenn and Isermann (2005), Isermann and Münchhof

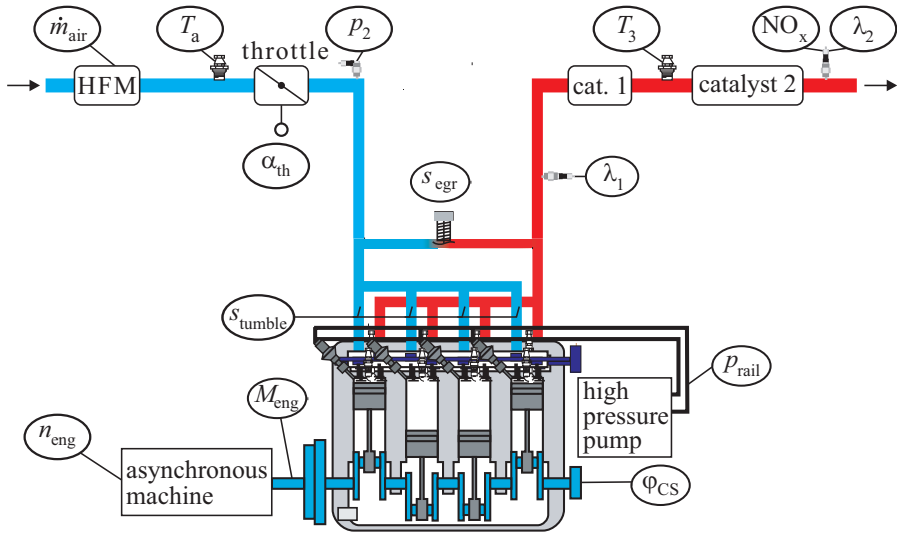


Fig. 4.1.2. Scheme of the DI gasoline engine with sensors. VW FSI 1.6l, 81 kW, 155 Nm.

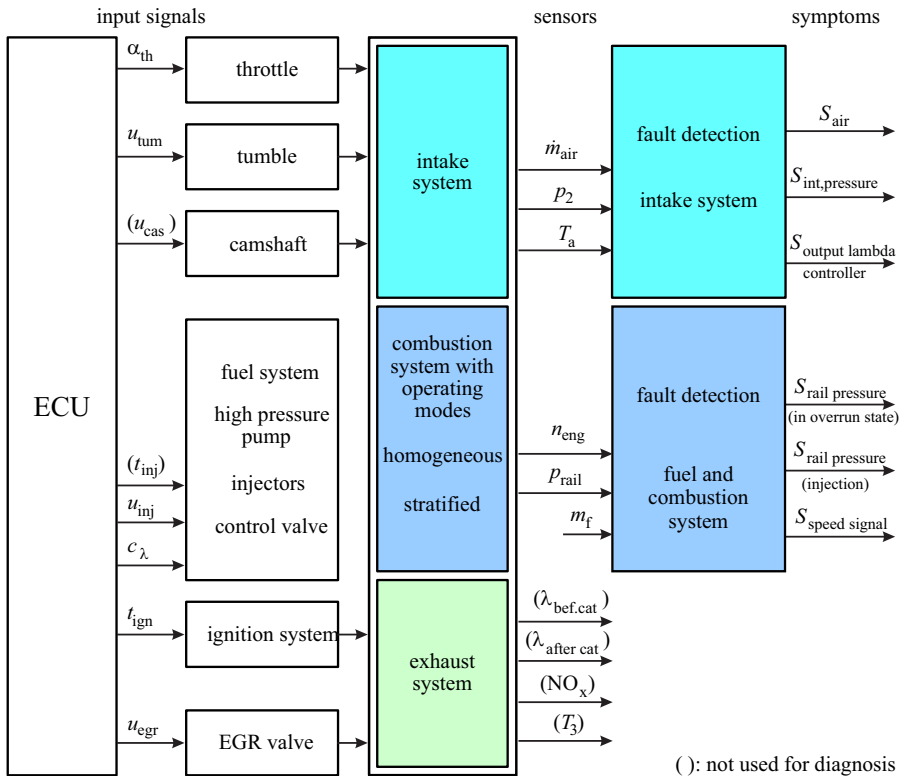


Fig. 4.1.3. Modular structure of the diagnosis system for the investigated DI gasoline engine.

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