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MODEL BASED FAULT DETECTION FOR THE INJECTION, COMBUSTION AND ENGINE-TRANSMISSION

Frank Kimmich [1], **Rolf Isermann**

[*] *University of Technology, Darmstadt*
Institute of Automatic Control

Abstract: New technologies, rising customer demands and severe exhaust gas regulations led to a rapid advancement of combustion engines. Nowadays, engines are characterized by more and more complex structures, whereby maintenance and trouble shooting becomes more and more complicated. Therefore the development of suitable fault detection and diagnosis methods is necessary, whereas the use of model based methods enhance a definite detection of faults according to type, size and location.

Keywords: Model Based Fault Detection and Diagnosis, Diesel Engine

1. INTRODUCTION

The increasing complexity of electronic controlled combustion engines with a rising number of actuators and sensors requires an improved and more extensive diagnosis for service companies as well as in the vehicle. More severe exhaust gas regulations with sharper exhaust gas limitations and rising requirements for on-board diagnosis of all emission relevant components reinforce these demands. Nowadays, modern on-board diagnosis systems are mainly based on simple threshold supervision or plausibility checks of measured signals as well as on signal based methods like the frequency analysis of the engine speed signal. In future these methods will no longer be sufficient for the increasing requirements. To keep up with this, model based fault detection methods developed and tested in recent years can come into operation. Analytical process information in form of mathematical process models is used to evaluate information of different sensors. Using process models existing dependencies between different signals can be utilized. By measuring of at least one input and corresponding output signal it becomes possible to draw conclusions on internal process variables, for instance parameters or state variables. Thus on numerical way the origin of faults can be detected and a separation and localization of faults can be achieved.

Figure 1 shows, in fault detection features are generated by an appropriate signal processing using pro-

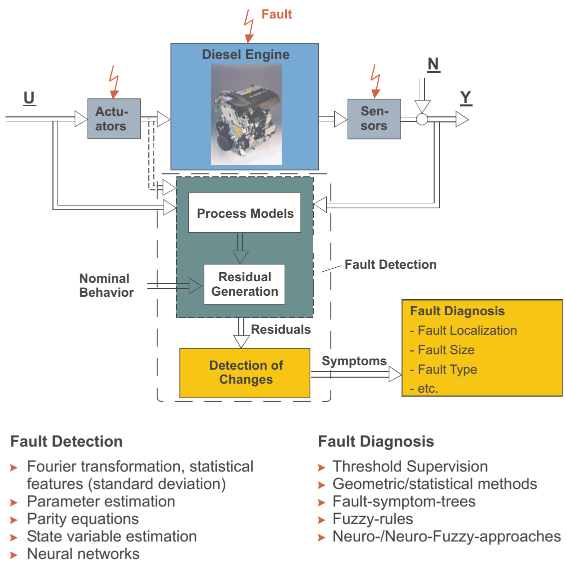

Fig. 1. General structure of model based fault detection and diagnosis

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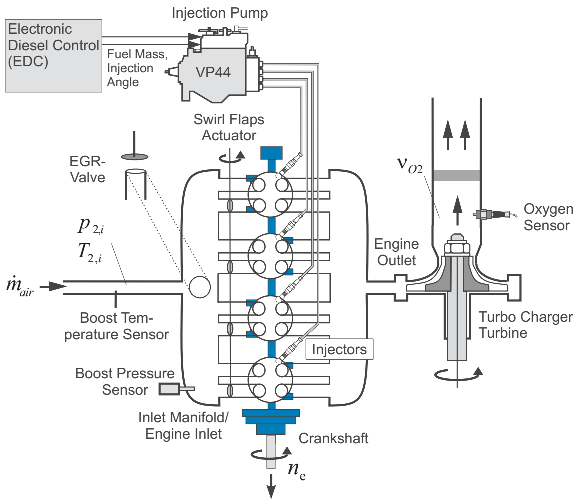

Fig. 2. Structure of the injection system, engine block and exhaust system

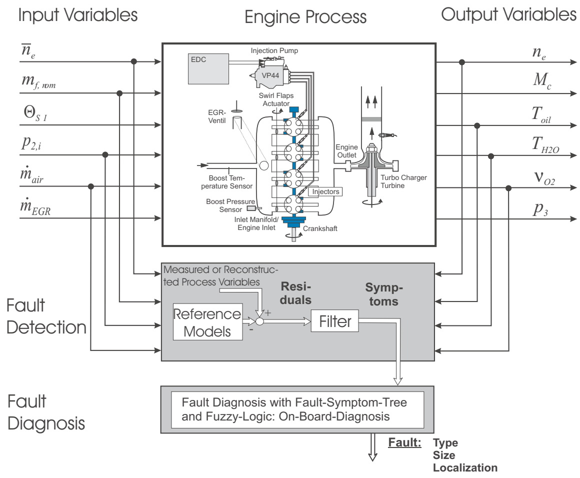

Fig. 3. Structure for model based fault detection of the injection, combustion and engine-transmission

cess models. The comparison of the features with the nominal behavior of the process leads to residuals. The detection of changes in the residuals results in symptoms. The following fault diagnosis processes the symptoms using fault diagnosis methods based on fault-symptom-causalities. The faults are located and fault causes are determined. Finally a weighting of the faults can be performed. For model based fault detection different methods can come into operation, for instance parameter estimation, parity equations, state variable estimation or neural networks. In the following fault diagnosis beside the classical threshold supervision and statistical weighting, fault-symptom-trees, fuzzy-rules or neuro-/neuro-fuzzy-approaches can be used. An overview can be found in (Isermann, 1994)

In the following contribution the principle of model based fault detection for diesel engines will be presented. Main focus will be put on detection methods for the injection, combustion and engine-transmission. The methods are based on engine speed analysis and oxygen evaluation in the exhaust gas. Residual and symptom generation will be shown.

2. MODEL BASED FAULT DETECTION FOR THE INJECTION, COMBUSTION AND THE ENGINE-TRANSMISSION

In (Kimmich *et al.*, 2001*a*; Kimmich *et al.*, 2001*b*) model based fault detection methods for the injection, combustion and engine-transmission were presented for a four cylinder diesel engine. The engine setup is depicted in figure 2. The aspirated air mass is applied to the cylinders by the induction system. Via an internal exhaust gas recirculation (EGR) exhaust gas is admixed to the aspirated air mass for keeping nitrogen oxide emissions low. By means of a high pressure injection pump VP44 the injection mass and injection timing is induced. Fuel pressures up to 1500 bar can be reached at the injection nozzle. The engine speed is measured at the open end of the crankshaft by means of an optical incremental transducer with a resolution of one degree crank angle ($°CA$). Behind the turbine of the turbo charger a broadband oxygen-sensor LSU (Bosch) is installed, which is used for measuring the oxygen concentration in the exhaust gas. This sensor is not a production sensor yet but advertised and serves as additional source of information about the combustion.

Figure 3 shows the structure of the fault detection system with the essential input and output variables of the engine process. The required process variables for the fault detection are the mean and high resolved ($1°CA$) measured engine speed signal $\overline{n_e}$ and n_e, the oxygen concentration in the exhaust gas ν_{O2}, the aspirated air mass $\dot{m}_{air}$, the boost pressure $p_{2,i}$, the engine temperature T_e, which corresponds to the mean value of oil (T_{oil}) and water (T_{H2O}) temperature and the nominal injection mass $m_{f,nom}$ of the electronic diesel control (EDC). Using parity equations the difference between the measured or reconstructed process variables and the process models, which represent the nominal process behavior, yields to the residuals. From engine speed evaluation the residuals mean effective engine torque r_{MME}, smooth engine operation r_{SEO} and four residuals from cylinder individual evaluation of smooth engine operation $r_{SEO1...4}$ result. The residuals injection mass r_{MF}, injection mass deviations $r_{\Delta MF}$ and four residuals from cylinder individual injection mass calculation $r_{MFC1...4}$ can be generated by evaluation of the oxygen concentration. By filtering the residuals, for instance with a threshold

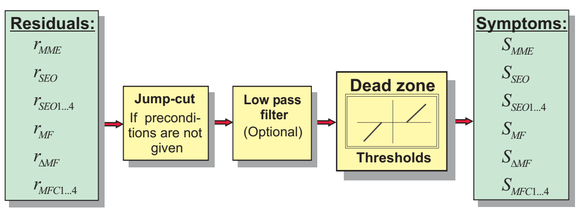

Fig. 4. Symptoms from residuals

function, the corresponding symptoms S result, see figure 4. Thereby the size of the threshold value is a compromise between robust fault detection against disturbances and the detection of small faults. In a next step the generated symptoms can then be used as input variables in a following fault diagnosis.

3. RESIDUALS FROM ENGINE SPEED EVALUATION

In the following the residuals from engine speed evaluation will be presented.

For generation of the residual mean effective engine torque r_{MME} the engine torque calculated by a process model is compared with the engine torque reconstructed from the engine speed oscillation (Kimmich *et al.*, 2001*a*; Kimmich *et al.*, 2001*b*; Kimmich and Isermann, 2002*a*). The torque model, which represents the nominal (fault free) engine, is based on the calculation of the mean effective cylinder pressure p_{me}, which can be split up into the mean indicated pressure of the low pressure part $p_{mi,LP}$, the mean effective pressure of the high pressure part $p_{mi,HP}$ and the mean friction pressure p_{mf}. In the following for each of the components a model is established.

In the model of the low pressure part the mean indicated cylinder pressure is calculated from the difference between boost pressure and exhaust gas pressure using a linear experimentally determined transfer function:

$$p_{mi,LP} = 1,47 \cdot (p_{2,i} - p_3(n_e, m_{f,nom})) - 0,14 \ . \quad (1)$$

In contrast to the boost pressure the exhaust gas pressure in equation (1) is not a measuring variable. Therefore it has to be reconstructed by a model. For this purpose a special neural network, a so called LOLIMOT-network (Local-Linear-Model-Tree-network) (Nelles, 1999), was trained using the available measuring data.

The model for the mean indicated cylinder pressure of the high pressure part is also based on a LOLIMOT-model, whereas the mean indicated pressure is calculated using the engine speed and the nominal injection mass of the EDC as input variables:

$$p_{mi,HP} = f(n_e, m_{f,nom}) \ . \quad (2)$$

According to (Fischer, 2000) the mean effective friction pressure is calculated dependent on the engine temperature and the engine speed using an empirical model approach:

$$p_{mf} = C_0 + C_1 \cdot \left(A_0(T_e) + A_1(T_e) \cdot n_e + A_2(T_e) \cdot n_e^2\right) , \quad (3)$$

with the parameters

$$A_i = f(T_e, T_e^2) \ .$$

For model adaption to different engines the parameters C_i are determined by specifying two reference values.

The mean effective pressure results from the individual pressure components, whereas the mean effective engine torque can be calculated considering the displacement volume V_d and the number of cylinders:

$$M_{me,mod} = \underbrace{(p_{mi,HP} + p_{mi,LP} - p_{mf})}_{p_{me}} \cdot \frac{V_d}{4\pi} \ . \quad (4)$$

On the other side the real released engine torque can be determined from the oscillation of the engine speed signal. In (Kimmich *et al.*, 2001*b*) it was shown that the amplitude of the engine speed oscillation is correlated with the released engine torque. To eliminate disturbances in the engine speed signal, for instance caused by measurement noise, first of all the signal is filtered by means of a Fourier series approximation. The approximation is each performed over one working cycle, whereas experiments have shown, that the speed signal can be approximated using only the forth engine harmonic corresponding to the ignition frequency. The delivered effective engine torque can be determined using a look-up table with the input variables mean engine speed and engine speed amplitude, see Figure 5.

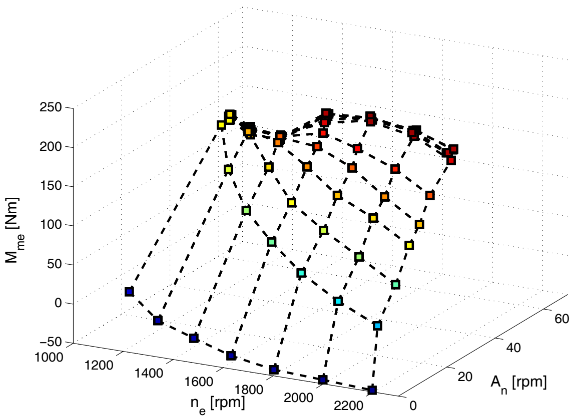

Fig. 5. Mean engine speed, amplitude of the engine speed oscillation and mean effective engine torque

With the reference model and the information of the real reconstructed torque the residual mean effective engine torque r_{MME} is defined as difference between reconstructed and model torque:

$$r_{MME} = M_{me,rec} - M_{me,mod} \ . \quad (5)$$

By means of a threshold detection the corresponding symptom S_{MME} results.

For supervision of smooth engine operation the mean acceleration of the crankshaft between successive combustions can be utilized according to (Schmidt *et al.*, March 6-9, 2000). The method is based on the fact that the change of kinetic energy over 180°CA -for four cylinder engines, this is the distance between two successive combustions- indicates the change of the delivered cylinder torque between the corresponding cylinders. Thereby a measure for the change of kinetic energy is the mean change of the angular acceleration in the accordant interval:

$$\Delta E_{kin}|_{\alpha}^{\alpha+\pi} = \frac{\theta_e}{\pi} \int_{\alpha}^{\alpha+\pi} \dot{\omega} d\varphi \;, \qquad (6)$$

whereas Θ_e is the inertia moment and π the considered interval of $180°CA$ in radiant. In crank angle domain equation (6) corresponds to a Crank Angle Synchronous Moving Average (CASMA) filter:

$$\Delta E_{kin}|_{\alpha}^{\alpha+\pi} = \frac{1}{\pi} \int_{\alpha}^{\alpha+\pi} \dot{\omega} d\varphi \cong \frac{1}{M} \sum_{i=0}^{M-1} \dot{\omega}((k-i)\Phi_s) \;, \quad (7)$$

whereas M corresponds to the number of sample points in the interval over $180°CA$ and Φ_s the sample angle. Because in production vehicles only the engine angular speed ω_e is available, the angular acceleration in equation (7) is determined from the engine speed signal:

$$\bar{\dot{\omega}}_E(k\Phi_s) \cong \frac{1}{M^2} \frac{\sum_{i=0}^{M-1} \omega((k-i)\Phi_s) - \sum_{i=0}^{M-1} \omega((k-i-M)\Phi_s)}{\pi} \cdot \sum_{i=0}^{M-1} \omega((k-i)\Phi_s) \quad (8)$$

For fault detection the so calculated mean angular acceleration is used as residual r:

$$r(k\Phi_s) = \frac{\bar{\omega}_e(k\Phi_s) - \bar{\omega}_e((k-M)\Phi_s)}{\pi} \bar{\omega}_e(k\Phi_s) \quad (9)$$

For stationary operation the mean angular acceleration is zero if no combustion differences occur. Faults like misfires or injection mass deviations lead to a deflection of the residual r accordingly. By elimination of the mean engine acceleration the method can also be used during dynamic driving operations. By corresponding evaluation of the residual, the residuals r_{SEO} and $r_{SEO1...4}$ as well as the symptoms S_{SEO} and $S_{SEO1...4}$ result.

4. RESIDUALS FROM OXYGEN EVALUATION

From oxygen evaluation in the exhaust gas the residuals injection mass r_{MF}, injection mass deviations $r_{\Delta MF}$ and cylinder individual injection mass $r_{MFC1...4}$ can be generated.

The residual injection mass is defined as difference between nominal injection mass by the EDC and reconstructed injection mass $m_{f,rec}$, which can be calculated from the oxygen concentration in the exhaust gas and the aspirated air mass. For the calculation a physical/chemical approach according to (Pischinger *et al.*, 1989) is used:

$$m_{f,rec} = \frac{m_{air} \cdot (1 - 4,76 \cdot \nu_{O2})}{14,5 + 4,553 \cdot \nu_{O2}} \;. \qquad (10)$$

Disturbances in the measured oxygen concentration or air mass are suppressed by low-pass filters. The residual results as follows:

$$r_{MF} = m_{f,rec} - m_{f,nom} \;. \qquad (11)$$

For the nominal case the results obtained with equation (10) are shown in figure 6. The relative deviation between nominal and calculated injection mass in percent is depicted for engine speeds from 1000 to 4000 rpm and nominal injection masses from 10 to 40 mg/stroke. As it can be seen the relative deviations are preponderant in a range of -10 to 10 percent except for low speeds and small injection masses. To define the nominal state for a fault detection system, figure 6 can be used as correction look-up table.

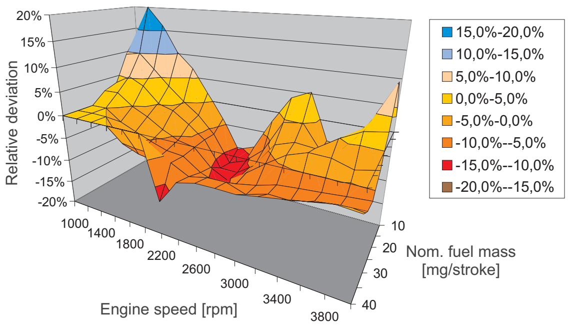

Fig. 6. Relative error between nominal and calculated injection mass

The residual injection mass deviation $r_{\Delta MF}$ is generated by a signal based method. Since the oscillation of the measured oxygen concentration over one working cycle ($720°CA$) is a measure for injection mass deviations between the individual cylinders, the standard deviation of the oxygen signal can be used as residual:

$$r_{\Delta MF} = \sigma_{\nu_{O2}} = \sqrt{\frac{1}{N-1} \sum_{i=0}^{N-1} (\nu_{O2}((k-i)\Phi_s) - \bar{\nu}_{O2}(k\Phi_s))^2} \qquad (12)$$

The residual is calculated after each working cycle, whereas in nominal case it is zero. If a predefined threshold is exceeded, the corresponding symptom $S_{\Delta MF}$ results and injection mass deviations are detected.

For cylinder individual injection mass calculation an inverse model of the sensor dynamics is used (Kimmich and Isermann, March 6-9, 2002*b*). Experiments have shown that the probe dynamics correspond to a PT_1 characteristic. Therefore rise time and gain have to be determined. For identification of the sensor dynamics it is assumed that no essential blending of the exhaust gas blocks among the individual cylinders take place, so that the oxygen concentration at the measuring point corresponds to an ideal step. Since the oxygen concentration is sampled crank angle synchronously, following equation can be set up to describe the inverse sensor model:

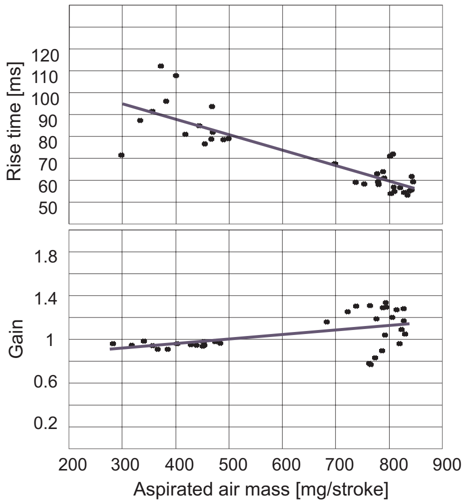

Fig. 7. Identified rise time and gain of the oxygen sensor

$$\frac{\nu_{O2,rec}(\zeta)}{\nu_{O2,m}(\zeta)} = G(\varsigma) = \frac{1+p_1\cdot\zeta^{-1}}{p_2}\ , \tag{13}$$

whereas $\nu_{O2,m}$ denotes the measured and $\nu_{O2,rec}$ the reconstructed and dynamic corrected oxygen concentration. The ζ-transfer function for crank angle synchronous systems corresponds to the z-transfer function for time discrete systems. In time domain rise time and gain results from the parameters p_1 and p_2 having regard to the engine angular speed ω_e and the sample angle Φ_s:

$$T = \frac{\Phi_s}{(p_1+1)\cdot\omega_E}\ , \quad K = \frac{T\cdot\omega_E\cdot p_2}{\Phi_s} \tag{14}$$

The model parameters were identified by means of a least square algorithm for different data sets. Figure 7 shows the results of the parameter estimation, whereas the values are plotted over the aspirated air mass, which indicates the different operating points. As it can be seen the rise time and the gain varies in dependency of the aspirated air mass, so that both variables have to be adapted over the operating range of the engine.

According to figure 7 the rise time of the oxygen sensor is in a range of 60 to 100 ms. Therefore it is too slow for cylinder individual measurement of oxygen concentration. Since the dynamic behavior of the sensor is known an inverse sensor model can be used to reconstruct the input signal without delays caused by the sensor dynamics. Using equation (10) and (13) as well as the identified parameters, the

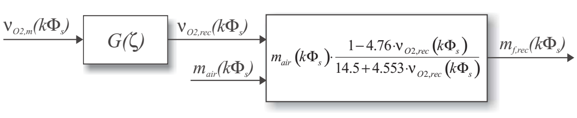

Fig. 8. Structure of cylinder individual injection mass calculation

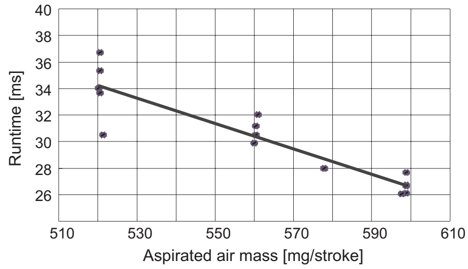

Fig. 9. Runtimes from the cylinder outlet to the oxygen sensor

cylinder individual injected fuel mass $m_{f,rec}$ can be calculated according to figure 8.

For cylinder assignment the runtime of the exhaust gas from the cylinder outlet to the measuring point has to be determined. Figure 9 shows the experimentally determined runtimes of the exhaust gas. With the inverse model of the sensor dynamics and the runtimes of the exhaust gas it is possible to evaluate the oxygen signal cylinder individually and to assign the reconstructed fuel mass to the corresponding cylinder. If the calculated fuel signal is evaluated around the top dead center (TDC) of each cylinder and compared with the nominal injection mass of the EDC, for each cylinder a residual cylinder individual fuel mass $r_{MFC1\ldots4}$ can be established as difference between nominal and reconstructed injection mass:

$$r_{MFC1\ldots4} = m_{f,rec1\ldots4} - m_{f,nom}\ . \tag{15}$$

5. EXPERIMENTAL RESULTS

In the following experimental results for the residuals engine torque, injection mass, injection mass deviations and cylinder individual injection mass are presented. The thresholds for symptom generation were determined experimentally at the test stand provided that a robust fault detection against disturbances as well as the detection of small faults is possible.

For the engine torque supervision in figure 10 an error in injection mass assignment and its effects on the amplitude of the engine speed oscillation is depicted. Starting from serial conditions (injection mass

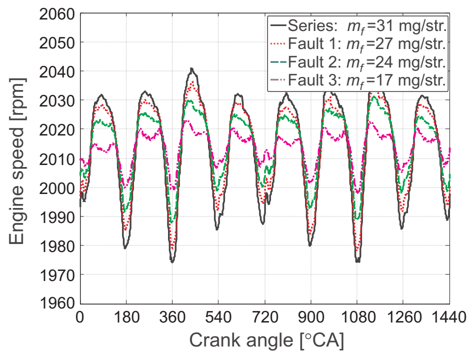

Fig. 10. Engine speed oscillation for different injection mass failures

$m_{f,nom} = 31$ mg/stroke, engine torque $M_{me} = 145$ Nm) an injection mass failure is implemented by incrementally reducing the injected fuel mass. The other state variables are kept constant, whereby the engine torque calculated from the torque model remains almost unchanged. In opposite to this with decreasing injection mass the delivered engine torque and there the corresponding engine speed amplitude decreases. Thus the residual differs significant from zero, which can be seen in figure 11. If the residual exceeds the depicted thresholds the corresponding symptom results.

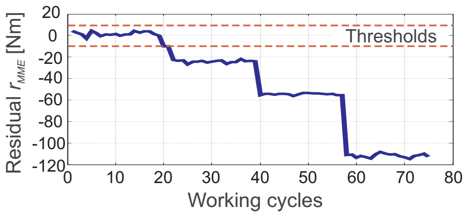

Fig. 11. Residual r_{MME} for different injection mass failures

For the residuals from oxygen evalutaion in figure 12 the oxygen concentration and the residuals for an injection mass failure in cylinder 1 at an engine speed of 2200 rpm and a nominal injection mass of 25 mg/stroke are depicted. Thereby after the second working cycle the injection mass in cylinder 1 was set to 15 mg/stroke. As it can be seen each of the residuals shows a deflection from zero. If a threshold limit is exceeded the fault can be detected and the symptoms results.

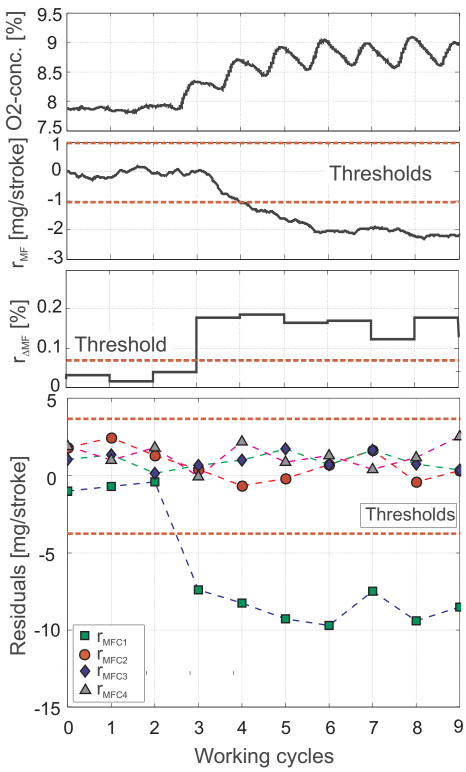

Fig. 12. Residuals from oxygen evaluation

6. SUMMARY AND CONCLUSIONS

In this contribution a model based fault detection system for the injection, combustion and engine-transmission for diesel engines was presented. Different methods based on engine speed and oxygen evaluation were discussed. From engine speed analysis residuals for engine torque and smooth engine operation supervision resulted. The evaluation of the oxygen concentration in the exhaust gas led to different residuals for injection mass supervision. The processing of the residuals by means of threshold functions led to the corresponding symptoms. Measurements showed the performance and the applicability of the presented methods.

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