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Detection of Exhaust Manifold Leaks on a Turbocharged SI-engine with Wastegate

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ABSTRACT

Emissions from modern SI-engines are reduced by a three way catalyst. However if there are leaks in the exhaust system before the catalyst emissions increase for two reasons. First the untreated emissions leak out. Second which is worse, due to waves in the exhaust system, oxygen leaks into the manifold and causes an oxygen sensor offset. The result is increased emissions as the air/fuel controller makes the engine run rich.

Here a method to detect leakages in the exhaust manifold is presented. The sensors used are binary oxygen sensor(s), intake manifold pressure and temperature, and the air mass flow sensor. Injection time is also used to estimate air/fuel ratio. Experimental results are shown with measurements from a turbo charged SAAB SI production engine with wastegate.

INTRODUCTION

The three way catalyst (TWC) reduces most of the emissions from modern spark ignited (SI) engines when it is operated at a stoichiometric air/fuel ratio [1, 2] as input. A leak in the exhaust system before the catalyst increases emissions for two reasons: First, untreated gases leak out. Second, due to waves in the exhaust system [3], oxygen can leak into the exhaust manifold and influence the measured λ.

The two cases are described in Figure 2 where exhaust manifold pressure is sampled with a high frequency for two different loads. In the lower plot of Figure 2 the minimum pressure is above ambient all time which results in a continuous leak of gases. The second case is shown in the top plot where the minimum pressure is below ambient pressure during approximately a quarter of the period. If a leak is present in this case oxygen would leak in and mix with the exhaust gases. The oxygen would also be transported away from the hole by the velocity of the gas. Gases leaking out of the hole is therefore not necessarily the same as the gases leaking in.

In the engine control system there is a closed loop air/fuel ratio PI-controller, with feed-back from the binary oxygen sensor. If oxygen leaks into the exhaust manifold it may cause wind up of the controller or a bias on the integrating part. Running less than stoichiometric also increases fuel consumption, carbon monoxide and dioxide emissions, and hydrocarbons. Using a rear oxygen sensor the engine control system can compensate for the excess air. The impact on emissions can be approximated given the maximum conversion efficiency. Emissions therefore increases proportional to the emissions before the TWC. To reduce the emissions a method to detect leakages before the first oxygen sensor is desirable.

Current methods for detecting leakages in the exhaust are e.g. listening to the engine sound, or filling the exhaust with smoke injected via the tail pipe and look for presence of smoke in the engine compartment. Here a computerized method to detect leakages in the exhaust manifold is presented. Detection is made possible by combining an observer based virtual exhaust manifold pressure sensor with estimated air/fuel ratio. A diagnosis framework, based on hypothesis tests [4] is then applied. Experiments with leakages are performed on a turbo charged SAAB SI production engine with wastegate. The sensors used are: binary oxygen sensor(s), intake manifold pressure and temperature sensors, and the air mass flow sensor. One actuator signal is also used, the injection time signal.

ANALYSIS OF THE IMPACT OF A LEAKAGE

For the case of emissions leaking out, an approximation is made to estimate how large diameter that is required to exceed the emission levels for EURO-3 and 4. In Figure 1 schematic of the system is shown. Given that the maximum allowed emission mass of species x after the TWC is lim_x and the conversion efficiency of the TWC is η_x. The maximum mass fraction L that can leak out is then given by the following inequality $L \leq \left(\frac{lim_x}{m_x} - 1\right)\frac{1}{\eta_x} + 1$. To give an estimate of the leakage fraction L, the efficiency of the TWC η_x is set to one. This results in $L \leq \frac{lim_x}{m_x}$. To estimate L a simulation of the EURO-3 driving cycle was performed using a longitudinal vehicle model of a SAAB 9^5. The model estimates the mean exhaust manifold pressure through the cycle. Leakage is then estimated given mean exhaust pressure together with Equation (1). With these assumptions the emission levels for EURO-3 is exceeded

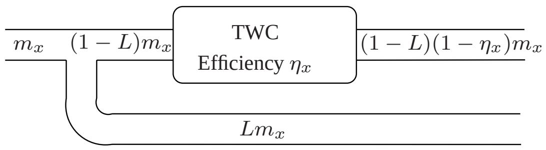

Figure 1: Given a mass of emissions m_x where x can be e.g. carbon monoxide. The mass fraction that passes through the leak is L and the conversion efficiency of the TWC for species x is η_x.

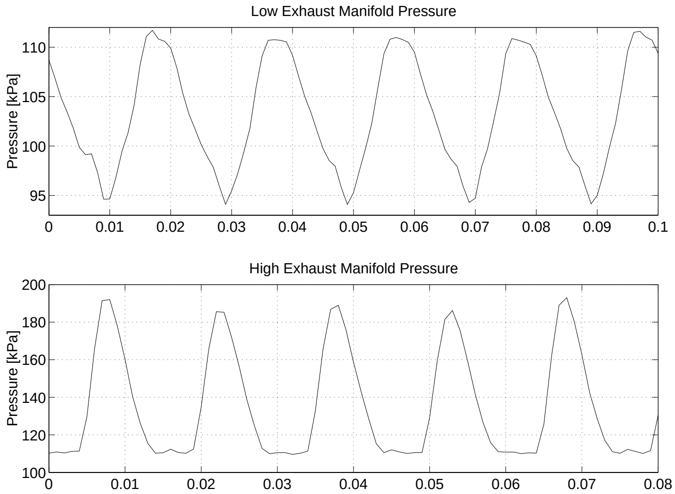

Figure 2: Exhaust pressure variations during the cycle. *Top:* The lowest part of the pressure wave is below ambient. This is referred to as low pressures. *Bottom:* All of the pressure wave is above ambient pressure and this case is referred to as high pressure.

by leakage out of a 6 mm hole and EURO-4 by a 4 mm leak.

DEFINITION OF LOW AND HIGH EXHAUST PRESSURE

The design of the diagnosis system is based on a partition of exhaust pressures into high and low pressures, see Figure 2. Lets start by observing that mean exhaust back pressure is almost linear in mass flow through the engine [1, 5]. The first case occurs when the minimum of the exhaust pressure waves are below ambient. If a leak is present here air leaks in. Hence *low pressure* will be used in the text to refer to operating points where the pressure in the exhaust manifold is below ambient for parts of the time. This condition is shown in the top of Figure 2.

High pressure appears when the lowest pressure is higher than the ambient pressure all the time, which is the case in the lower plot of Figure 2. A leak in this case will cause emissions to leak out all the time and hence the exhaust manifold pressure to drop.

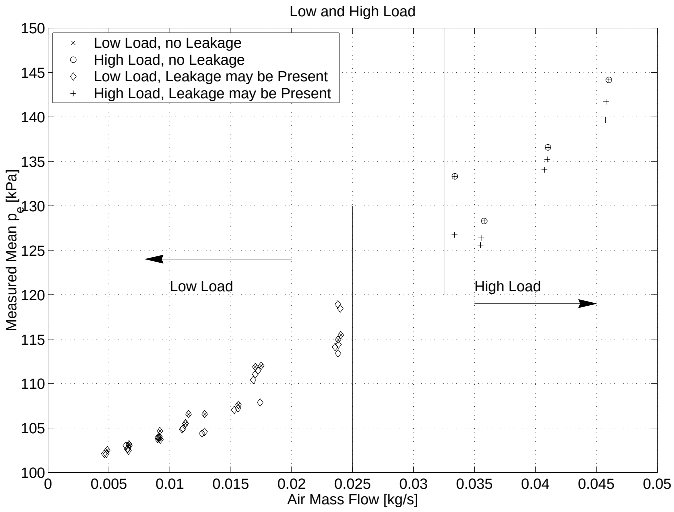

Figure 3: Mean exhaust manifold pressure plotted against air mass flow for low and high exhaust manifold pressures. There is a distinct border between the selected limits for high and low load, which is shown as vertical lines in the plot above. For low loads the lowest exhaust manifold pressure is below 98 kPa and for high loads the lowest pressure is above 102 kPa.

Using Air Mass Flow to Partition Exhaust Pressure

Low pressures are defined from measurements as where the minimum exhaust manifold pressure was below 98 kPa and high pressures are defined for pressures above 102 kPa. The limits are here arbitrarily chosen as ambient pressure is approximately 100 kPa and a limit of $\pm$ 2 kPa is added. The instantaneous pressure is not easily obtained and the mean exhaust manifold pressure depends strongly on the mass flow through the engine. The result is shown in Figure 3. For air mass flows less than 25 g/s the lowest exhaust manifold pressure was below 98 kPa and for air mass flows above 32.5 g/s the minimum exhaust manifold pressure was over 102 kPa. Flows in between theses limits are not categorized as low or high using this method. However this categorization captures the majority of the operating conditions.

DESIGN OF DIAGNOSIS SYSTEM

To diagnose the leakage a framework with hypothesis tests is used [4]. First the statements of the diagnosis system is decided:

Abbreviation	Explanation
NF	No fault
EML	Exhaust Manifold Leakage

Fault modes are initially described in words and then models are presented for the two statements. As the system behaves differently depending on exhaust manifold pressure there are two cases. One for low pressures, where air can leak into the exhaust manifold. The second case is for high pressures where exhaust gases continuously leak out. To apply the methodology some assumptions are made regarding the system needed

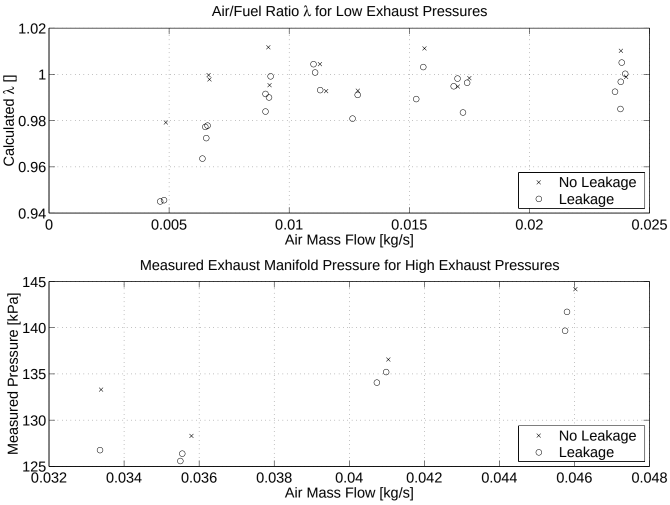

Figure 4: *Top:* Calculated air/fuel ratio. When there is a leakage the extra oxygen results in a richer mixture to the engine. *Bottom:* Exhaust manifold pressure for the different measurements. When there is a leak present at high mass flows the exhaust pressure will drop slightly. Here it drops at most 9 kPa.

to design the test statistics.

No Fault (NF)

Depending on the exhaust manifold pressure two cases have to be considered:

Low pressures No oxygen present in the exhaust gases.

High pressures There is no exhaust manifold pressure drop compared to what was expected.

Exhaust Manifold Leakage (EML)

As for the no fault state there are two cases:

Low pressures Oxygen is present in the exhaust gases.

High pressures Due to the increased flow of gases out of the exhaust manifold the pressure drops compared to the fault free case.

Assumptions

First the engine is assumed to be run stationary, that is the same speed and load is held constant for approximately 20 seconds. The engine models are only valid for a warmed up engine and the TWC does not work for a cold engine, which means that a warmed up engine is required. The discrete oxygen sensor is only useful if the engine runs stoichiometric and this will also be required. Measured data is time discrete and the samples are assumed to be independent.

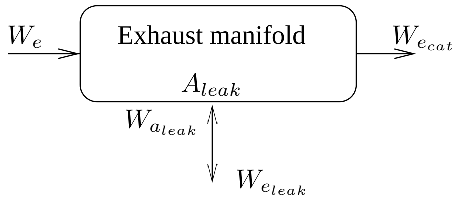

Figure 5: Model of leakage in the exhaust manifold. Exhaust gases coming from the engine are W_e and are passing through the exhaust manifold. A leak with area A_{leak} may cause air to leak in, $W_{a_{leak}}$ or emissions to leak out, $W_{e_{leak}}$. The gases, $W_{e_{cat}}$, are then passed on to the front oxygen sensor and then to the catalyst.

FAULT MODELS

Faults are described by a model to which the measured or estimated data are tested against. If the fault model explains the data the statement of the diagnosis system can be decided. In this case fault models are developed for the fault free case (NF) and for the exhaust manifold leakage case (EML).

When the models of the faults are fixed, test statistics are developed for the fault model. A test statistic is a function of the sampled data. A framework of hypothesis tests are then applied to the test statistic. For a description of the symbols used, please see the nomenclature at the end. First the exhaust manifold leakage model is described.

Exhaust Manifold Leakage Model

As mentioned earlier for low pressures in the exhaust manifold air may leak in. For this purpose a model of the oxygen content is desired for low pressures. Information of the oxygen content in the exhaust manifold is supplied by the binary oxygen sensor(s).

For higher exhaust pressures there is a constant flow out of the exhaust manifold causing a drop in exhaust manifold pressure. Here a virtual pressure sensor is used to detect the change in pressure without introducing any new sensors. Changes in exhaust manifold pressure is called p_{em_Δ}, and p_{em} is calculated below:

$$p_{em} = p_{e_{expected}} + p_{em_\Delta}$$

Depending on the pressure ratio, $\pi = \frac{p_{em}}{p_a}$, between the exhaust manifold and the ambient air may flow into the exhaust manifold or exhaust emissions flow out. A straight forward approximation is to assume that the exhaust gas is an ideal gas flowing through a restriction with area A_{leak}.

If the exhaust pressure is larger than the ambient pressure emissions will flow out

$$W_{e_{leak}} = \frac{p_{em}}{\sqrt{R_e T_{em}}} \Psi \left(\frac{1}{\pi} \right) A_{leak} C_d, \quad \pi > 1 \qquad (1)$$

The other case occurs when the ambient pressure is higher than the exhaust manifold pressure and air leaks into the exhaust manifold.

$$W_{a_{leak}} = \frac{p_a}{\sqrt{R_a T_a}} \Psi(\pi) A_{leak} C_d, \quad \pi < 1 \tag{2}$$

$$\Psi(\pi) = \begin{cases} \sqrt{\frac{2\gamma}{\gamma-1}\left(\pi^{\frac{2}{\gamma}} - \pi^{\frac{\gamma+1}{\gamma}}\right)} & \text{for } \pi > \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \\ \sqrt{\frac{2\gamma}{\gamma-1}\left(\left(\frac{2}{\gamma+1}\right)^{\frac{2}{\gamma-1}} - \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\right)} & \text{otherwise} \end{cases}$$

Exhaust Pressure Difference Model

For higher mass flows the minimum exhaust pressure is above the atmospheric pressure and therefore exhaust gases will leak out continuously. This constant leak will decrease the exhaust manifold pressure, which can be modeled using the first law of thermodynamics [6]. Exhaust manifold pressure influences the mass of residual gases remaining in the cylinder at exhaust valve closing (EVC). The mass of air that can fill the cylinder depends on, among others, the mass of residual gases. More residual gas mass results in less air mass to the cylinder and the other way around.

The derivation of exhaust manifold pressure using sensors on the intake side can be briefly described as follows. Calculate whether the cylinder is filled with the expected mass of air. If not the offset m_Δ will differ from zero, see Equation (3a). Since the air mass offset m_Δ is influenced by the exhaust manifold pressure [6] a corresponding change in exhaust manifold pressure can be estimated, Equation (3b).

$$m_\Delta = \underbrace{\eta_{\text{vol}}(N, p_{im}) \frac{p_{im} V_d}{R_c T_{im}}}_{\text{Expected air mass}} - \underbrace{W_{at} \frac{n_r}{N}}_{\text{Measured air mass}} \tag{3a}$$

$$p_{em_\Delta}(T_{im}, m_\Delta) = -k T_{im} m_\Delta \tag{3b}$$

In Equation (3b) k is a constant which is identified using a least square technique.

Oxygen Content Model

For the fault free case (no leakage) the influence of a leakage could be approximated using measurements of the pressure waves in the exhaust and measured air mass flow:

$$\lambda_{new} \approx \frac{1}{\left(\frac{A}{F}\right)_s} \frac{W_c + W_{a_{leak}}}{W_f} = \lambda_{\text{no leak}} \frac{W_c + W_{a_{leak}}}{W_c} \tag{4}$$

For the measurements in Figure 2 with application of Equations (2, 4) the change in air/fuel ratio can be approximated, see Figure 6. In the approximation of flows in and out of the manifold $C_d = 1$ was used in Equation (1) to give an approximation of the leakage. A known disturbance in this experiment was that only 0.5 second of measured data was used to estimate the leakage flow of air into the exhaust manifold.

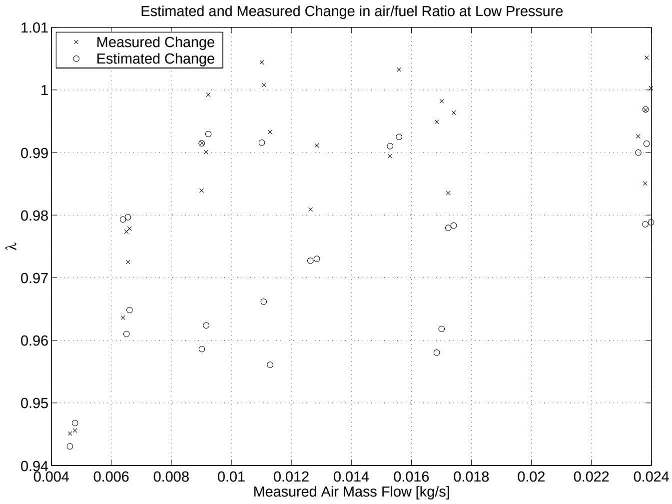

Figure 6: Estimated changes in λ in percent for different loads and leakage areas (4 mm and 5 mm diameter leaks). The estimated change in λ is of the same magnitude as the measured.

Since the lambda sensor is sensitive to oxygen in the exhaust gases and the lambda-controller has an integration part which stores information of the air/fuel ratio. The result is an offset in the integrating part of the air/fuel controller during a leak. Two sources are candidates for information on offsets from the stoichiometric: First the integrating part of the air/fuel ratio controller. Second source is estimated air/fuel ratio using measured air mass flow and injection time. Which of these methods is most suitable for detection of oxygen leaking into the exhaust manifold?

Lets start with the integration part of the air/fuel ratio controller. The advantage of this information is that no additional computations are necessary as this information is already available in the control unit. In ECUs there are also some model describing the mass of fuel to be injected given information of intake manifold pressure and temperature, engine speed, and measured air mass flow. This kind of information is often represented by an engine map. If some kind of stationary error is present in this map it is handled by the feed-back from the oxygen sensor. However the error in the map then shows up in the integrating part of the air/fuel ratio controller which is a less desirable property. Another drawback is that the integrating part may also be influenced by the rear oxygen sensor. Especially if there is a leak of oxygen disturbing the front sensor, the rear sensor information will indicate presence or absence of oxygen. If the value of the integrator is to be used, detailed knowledge of the rear sensor feed back is necessary.

The second method is to use knowledge of measured air mass flow and injection time to estimate the current air/fuel ratio called λ_{calc}.

$$\lambda_{\text{calc}} = \frac{W_{at}}{\left(\frac{A}{F}\right)_s K_{\text{inj}}(t_{\text{inj}} - t_0) \frac{N}{n_r}} \tag{5}$$

Here additional knowledge of stoichiometric air/fuel ratio is necessary as well as a model of the injector. One major advantage is that the air/fuel ratio still can be calculated regardless of how the front and rear feed back from the oxygen sensors influences the controller. This means that no information of how controllers are implemented is necessary. A disadvantage is that it has two additional parameters K_{inj} and t_0. Model errors in K_{inj} has the same impact as errors in the stoichiometric air/fuel ratio $\left(\frac{A}{F}\right)_s$. Errors in the needle lift time t_0 are most evident for small injection times which unfortunately is the case for low exhaust pressures where the air mass flow is low.

A drawback of the later method is its sensitivity to fuels with different stoichiometric air/fuel ratio $\left(\frac{A}{F}\right)_s$. To ensure proper operation of the method a known fuel is necessary. Since the second method with estimated air/fuel ratio is independent of the implementation of the air/fuel ratio controller it is chosen as method to detect presence of oxygen. However if the stationary errors in the ECU engine maps are small and detailed knowledge exists of how rear sensor feed-back influences the value of the integrator it is the desirable method. The reason is that it has a possibility to handle changes in fuel by combining information from the front and rear oxygen sensor.

Design of Test Statistics

Two test statistics are used. First for the oxygen content the mean of λ_{calc} is as a test statistic. The second is the estimated exhaust manifold pressure change p_{em_Δ}. Both test statistics are modeled as constant parameters μ_x. The parameter is estimated from a measured signal $y(t)$, which is subjected to noise $v(t)$ originating from measurements and model errors. Noise is assumed to have a normal distribution $N(0, \sigma_v)$ and to be independent. Time discrete measurements are used to estimate the constant parameter. As estimate of the constant parameter μ_x, the mean value of the measured signal $y(t)$ is used. The estimated parameter is called $\hat{\mu}_x$.

$$\hat{\mu}_x = \frac{1}{N}\sum_{i=1}^{N} y_i = \mu_x + \frac{1}{N}\sum_{i=1}^{N} v_i \sim N(\mu_x, \frac{1}{\sqrt{N}}\sigma)$$

The standard deviation of the estimate $\hat{\mu}_x$ is $\sigma_{\hat{\mu}_x} = \frac{\sigma_v}{N}$.

Low Exhaust Pressures Here the estimate of oxygen content is modeled using the mean value of sampled λ_{calc} as a parameter.

$$\overline{\lambda_{\text{calc}}} = \frac{1}{N}\sum_{i=1}^{N} \lambda_{\text{calc}\,i} \tag{6}$$

High Exhaust Pressures Estimates of changes in exhaust manifold pressure from expected pressure is made by the virtual exhaust manifold pressure sensor p_{em_Δ}. The change is estimated as the mean value of estimated pressure changes.

$$\overline{p_{em_\Delta}} = \frac{1}{N}\sum_{i=1}^{N} p_{em_\Delta\,i} \tag{7}$$

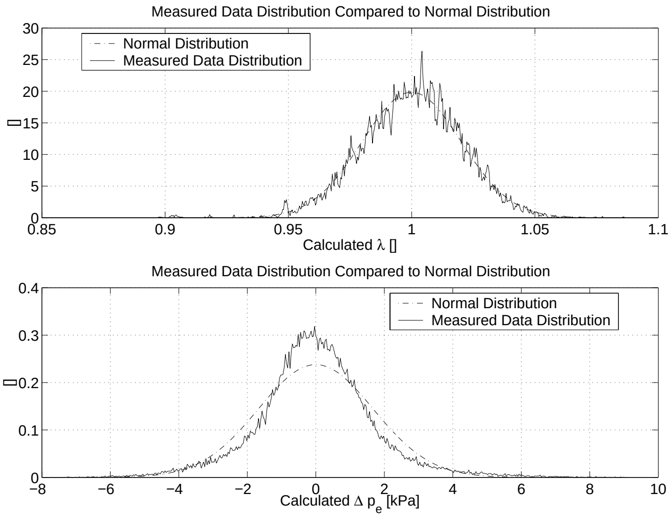

Figure 7: *Top:* Distribution of $\overline{\lambda_{\text{calc}}}$ in the fault free case. A normal distribution was assumed. *Bottom:* Exhaust manifold pressure distribution in the fault free case. Values have been calculated for different stationary operating points. The shape resembles that of a normal distribution.

Hypothesis Tests

The present fault is denoted F_p and a hypothesis test is formulated to test whether there is a leakage in the exhaust manifold present (EML) or if no fault is present (NF).

$$H_0 : F_p \in \{NF\}$$
$$H_1 : F_p \in \{EML\}$$

This corresponds to test whether the variable is within a specified region or not. If it is within the specified region the null-hypothesis H_0 can not be rejected. A threshold, denoted J, will be used to suppress noise and model errors. Value of the threshold is calculated using theory from statistical hypothesis tests [7]. A significance level of 0.5% is used in the decision of the thresholds. The selected threshold is a compromise between missed detections and false alarms. The missed detection rate decreases as the false alarm rate increases and vice versa.

Low Exhaust Pressures For low pressures the oxygen content is tested using:

$$\overline{\lambda_{\text{calc}}} < J_{\overline{\lambda_{\text{calc}}}} \tag{8}$$

If $\overline{\lambda_{\text{calc}}}$ is above $J_{\overline{\lambda_{\text{calc}}}}$ no conclusion can be drawn. Exhaust manifold leakage can be present if $\overline{\lambda_{\text{calc}}}$ is below the threshold as it indicates the presence of oxygen in the exhaust. The distribution of $\overline{\lambda_{\text{calc}}}$ in the fault free case is shown in the top of Figure 7 together with an approximation of a normal distribution $N(1, 0.02)$. With the desired significance level the normal distribution gives the threshold $J_{\overline{\lambda_{\text{calc}}}} = 0.95$.

High Exhaust Pressures At higher exhaust manifold pressures, the pressure drop compared to the no leak case is studied. If the pressure in the exhaust manifold is lower than a specified

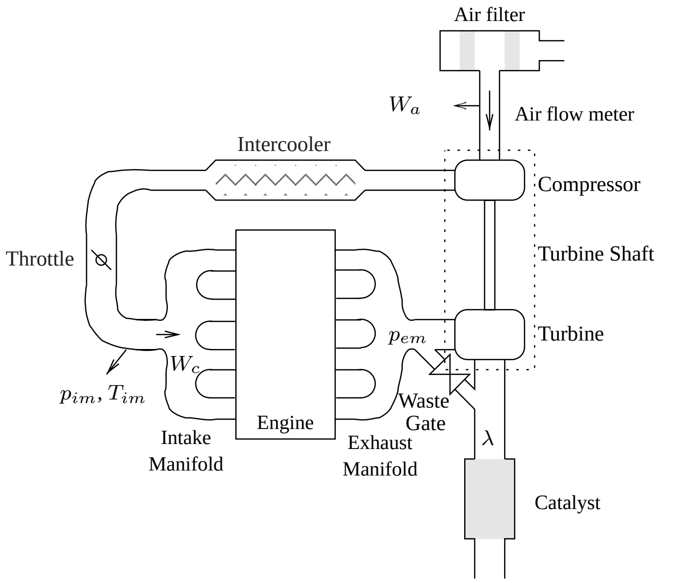

Figure 8: Engine Schematic

threshold a leakage could be present.

$$\overline{p_{em_\Delta}} < J_{\overline{p_{em_\Delta}}} \quad (9)$$

To decide the value of $J_{\overline{p_{em_\Delta}}}$ the distribution of $\overline{p_{em_\Delta}}$ in the fault free case was studied, see the lower plot in Figure 7. A normal distribution was assumed and hence $\overline{p_{em_\Delta}} \sim N(0, 1.7)$. With the desired significance level the threshold was set to $J_{p_{em_\Delta}} = -4.3$ kPa.

Diagnosis Decision

In the diagnosis system there is one hypothesis test and two test statistics used depending on the exhaust pressure (low or high). The test is rejected when the test statistic is within the rejection region, $\mu_x > J_x$, and the decision is EML. If the test is not rejected the presence of an exhaust manifold leakage can not be dismissed, and the decision is NF.

EXPERIMENTAL SETUP

In Figure 8 a sketch of the engine used is shown. It is a 2.3 dm^3 turbo charged SAAB 9[5] engine with additional sensors for pressure and temperature. In the exhaust system there is only one production sensor before the catalyst and that is the oxygen sensor.

The engine is equipped with additional pressure sensors in the intake system before the throttle and in the intake manifold. Pressure sensors are also present in the exhaust system before and after the turbine There are also extra temperature sensors of PT200 type, in the intake manifold, between the intercooler and the throttle, and in the exhaust manifold close to the turbine. All measurements are performed with a VXI-based instrument HPE-1415A.

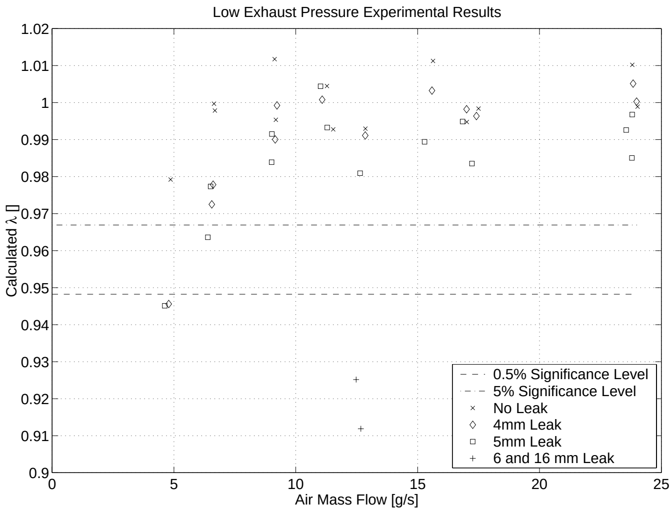

Figure 9: Experimental results using calculated $\overline{\lambda_{\text{calc}}}$ for low loads. The lines indicate different significance levels. No false alarms are present but only 15% of the leakages are detected.

The engine is connected to an asynchronous Dynas 220 NT dynamometer, which is operated in constant speed mode. The dynamometer is controlled by a PC and the engine is controlled by a research engine management system called Trionic 7. The engine management unit is connected to a PC in the control room using a CAN-bus.

EXPERIMENTAL RESULTS

The research engine is equipped with an exhaust manifold with additional plugs in which leakages can be introduced. Leakages are created by removing a plug or replace it with another plug with a drilled hole. The leakage is applied on the exhaust manifold of cylinder 3. In the measurements the engine is run stationary for 25 seconds to allow for temperatures and controllers to stabilize. Data is then sampled for 30 seconds which was used to evaluate the diagnosis system.

Low Pressures

For low pressures the estimated air/fuel ratio $\overline{\lambda_{\text{calc}}}$ is the evaluated test statistic and the result is shown in Figure 9. For low pressures there are no false alarms but the missed detection rate is 85% for these small leakages.

The use of estimated air/fuel ratio λ_{calc} requires a defined fuel, since different fuels may not have the same stoichiometric ratio. An example of such disturbance is fuels which contains of alcohols. A changed air/fuel ratio causes the estimated λ_{calc} to deviate from its nominal value and cause either a missed detection or a false alarm. The outcome depends on the direction of air/fuel ratio change. Fuels with lower $\left(\frac{A}{F}\right)_s$ increases the risk of false alarms and fuels with higher $\left(\frac{A}{F}\right)_s$ increases the rate of

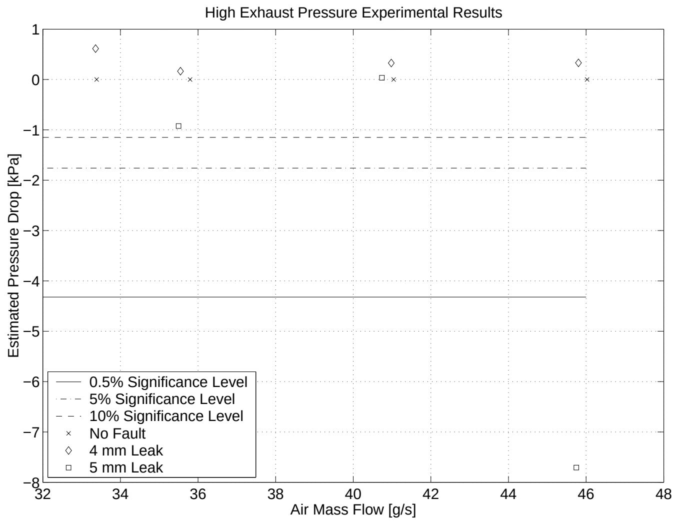

Figure 10: Experimental results using estimated exhaust manifold pressure drop. No false alarms are encountered, but only one leakage is detected.

missed detections.

High Pressures

At higher exhaust manifold pressures the estimated pressure drop $\overline{p_{em_\Delta}}$ is the evaluated test statistic and the experimental results are shown in Figure 10. Here only one leakage is detected and that is one that differs significantly from the other measurements, which indicates that it may be an estimation error since the pressure drop for the surrounding operating points does not show this behavior. The missed detection rate was also here 85%.

The virtual exhaust manifold pressure sensor relies on information from the air mass meter and sensors in the intake manifold. Changes and uncertainties in the sensor readings causes errors in the estimation of exhaust manifold pressure. This can also result in missed detections or false alarms.

FUTURE WORK

The suggested method shows promising results for low exhaust manifold pressures. At higher pressures more data is needed to study the behavior of the exhaust manifold pressure. Another interesting topic is how to merge the information from low and high exhaust manifold pressures and make the diagnosis decision based on information fusion.

CONCLUSIONS

A diagnosis method for detecting leakages in the exhaust manifold have been developed using the estimated air/fuel ratio and a mean value model of the exhaust manifold pressure. A hypothesis test is used to decide whether there is a leak or not. The use of hypothesis tests features a possibility to suppress noise and modeling errors by setting a significance level of the test. The first results are encouraging but the experiments are not conclusive yet.

Low Pressures

For low exhaust manifold pressures, the oxygen content of the exhaust gases is monitored. An increase in oxygen indicates a leakage. Detection of exhaust manifold leakage has successfully been shown for even small leakages (4mm diameter). The missed detection rate is high but detections are made at low engine loads. The method is very sensitive to fuel changes as it estimates the current air/fuel ratio, but it is independent of the implementation of the air/fuel controller and feed back from a rear oxygen sensor.

High Pressures

At high exhaust manifold pressures, there is a continuous flow out of the exhaust manifold causing the pressure to drop, which can be detected using a virtual exhaust manifold pressure sensor. Exhaust manifold pressure estimation relies on accurate sensors on the intake side together with an good description of the volumetric efficiency. No additional sensors in the exhaust manifold are necessary. More validation data is however needed as the system was not sufficiently excited.

ACKNOWLEDGMENTS

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NOMENCLATURE

Symbol	Description
m_x	Raw emission mass of specie x, e.g. carbon monoxide.
η_x	Efficiency of the TWC for the specie x
lim_x	Emission regulation for specie x. Specifies maximum allowed mass of specie x.
L	Mass fraction of total emissions that leaks out of an exhaust manifold leakage.
p_{im}	Intake manifold pressure
p_{em}	Exhaust manifold pressure
p_{em_Δ}	Exhaust manifold pressure difference from nominal (no leaks).
$\overline{p_{em_\Delta}}$	Mean value of exhaust manifold pressure difference from nominal (no leaks).
m_Δ	Difference in air to cylinder from expected.
π	Pressure ratio
J_x	Threshold in the hypotheses tests.
T_{im}	Temperature of gases inside the intake manifold
T_{em}	Temperature of gases inside the exhaust manifold
T_a	Ambient air temperature
η_{vol}	Volumetric efficiency
W_a	Measured air mass flow
W_{at}	Air mass flow through throttle
W_c	Air mass flow to cylinder
W_f	Fuel mass flow
C_d	Discharge coefficient
m_Δ	Air mass to cylinder offset, calculated using mapped volumetric efficiency
λ	Normalized air/fuel ratio
λ_{calc}	Estimated air/fuel ratio
$\overline{\lambda_{\text{calc}}}$	Mean value of estimated air/fuel ratio
$\left(\frac{A}{F}\right)_s$	Stoichiometric air/fuel ratio
V_d	Displacement volume
n_r	Number of revolutions per cycle
N	Engine speed i revolutions per second
t_{inj}	Time in seconds where the injector is open
K_{inj}	Maximal delivered fuel mass per second
t_0	Time in seconds for the injector needle lift