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Leakage detection in a fuel evaporative system

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ABSTRACT

On-board diagnostic (OBD) regulations require that the fuel system in personal vehicles must be supervised for leakages. Legislative requirement on the smallest leakage size that has to be detected is decreasing and at the same time the requirement on the number of leakage checks is increasing. A consequence is that detection must be performed under more and more diverse operating conditions. This paper describes a vacuum-decay based approach for evaporative leak detection. The approach requires no additional hardware such as pumps or pressure regulators, it only utilizes the pressure sensor that is mounted in the fuel tank. A detection algorithm is proposed that detects small leakages under different operating conditions. The method is based on a first principles physical model of the pressure in the fuel tank. Careful statistical analysis of the model and measurement data together with statistical maximum-likelihood estimation methods, results in a systematic design procedure that is easily tuned with few and intuitive parameters. The approach has been successfully evaluated on a production engine and fuel system setup in a laboratory environment.

1. Introduction and problem formulation

Environmentally based legislation, for example the Californian CARB regulations (CARB, 2002), states that the on-board diagnostic (OBD) system must monitor the fuel system to ensure that vapor does not leak into ambient air. One can expect that federal and also European regulations have, or will in the future, have similar requirements. A principle sketch of a common fuel system setup is shown in Fig. 1. The system includes a carbon canister which is connected in one end to the fuel tank and in the other end to the ambient air. The system has a diagnosis valve which is open during normal operation of the engine, and closed when diagnosis is performed. A purge valve connects the canister to the intake manifold of the engine. The canister is regularly purged from hydrocarbons when the purge valve is opened, causing a flow of air through the canister and into the engine where the fuel vapor is combusted. The fuel tank is equipped with a pressure sensor that measures the difference in pressure between ambient air and the fuel tank pressure.

The on-board diagnostics system shall monitor the complete evaporative system for vapor leaks to the atmosphere. Currently the legislative detection requirements move to smaller and smaller leakages. The Californian CARB regulations state that for vehicles with model year 1996 and later, leakage orifices as small as 0.040 in (1 mm) in diameter must be detected and as of year 2000, the requirement is tightened and detection of leakages as small as 0.02 in (0.5 mm) is required (CARB, 2002). In 2005, CARB updated the OBDII regulations such that leak detection checks have to be performed more frequently which also means that detection must be performed under more diverse operating conditions. This will require development of existing methods for leakage supervision (Kobayashi et al., 2004).

Roughly, one can say that there exists two main principles for leakage monitoring: vacuum decay and pressure decay principles. With the vacuum-decay principle, an underpressure is created in the fuel tank compared to the ambient pressure and the decay of the pressure difference is monitored and analyzed. The pressure decay principle creates an overpressure in the fuel tank and the pressure difference is monitored and analyzed.

The two principles have their own set of advantages and disadvantages. A disadvantage with pressure decay methods is that, in case of a leak, the overpressure presses fuel vapor out into the atmosphere while in a vacuum decay the air flow is into the fuel tank and thus vacuum-decay methods are considered environmentally more safe. In addition, pressure decay methods are reported to have a heightened risk of explosion (Remboski, Plee, Woznick, & Foley, 1997). Also, pressure decay methods require an extra component, a pump to pressurize the fuel tank. The advantage with a pressure decay method is that it has been reported to give higher performance in detecting smaller leakage orifices (Perry & Delaire, 1998).

Typical requirements on a supervision system are low cost and high accuracy. Also, since regulations require that leakage detection checks are performed more frequently, there is also a need for the detection algorithm to be fast and applicable in different operating conditions. Based on this discussion, this work

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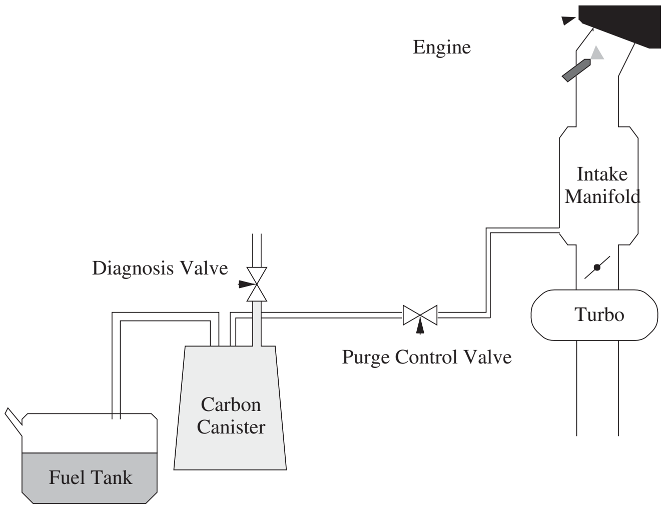

Fig. 1. The evaporative purge system.

presents a new vacuum-decay method based on analyzing the differential pressure in the tank. A vacuum-decay method is used since it is inexpensive and requires little extra instrumentation, for example no extra pump or an absolute pressure sensor. A key component of the method is a physically based model of the pressure in the fuel tank. Careful use and statistical analysis of the model enables fast and reliable diagnosis under different operating conditions. This work relies on the model developed in Andersson and Frisk (2001), where another leakage detection method was proposed. One main difference between Andersson and Frisk (2001) and this work is that here a thorough statistical analysis of the problem enables a systematic design procedure with fewer tuning parameters. The method in this paper also handles the fact that the air partial pressure in the tank is unknown and non-constant during a leakage, which was not possible in the approach proposed in Andersson and Frisk (2001). Finally, it is shown in Section 5 that the method proposed in this paper has a significantly better leak detection performance than the method presented in Andersson and Frisk (2001).

Section 2 describes the system and its operation to detect leakages. Section 3 describes the physically based model for the tank pressure signal and Section 4 then describes how this model is used in a detection algorithm. The proposed detection algorithm is evaluated in Section 5 on measured data from a standard production engine fuel system setup. A concluding discussion is given in Section 6.

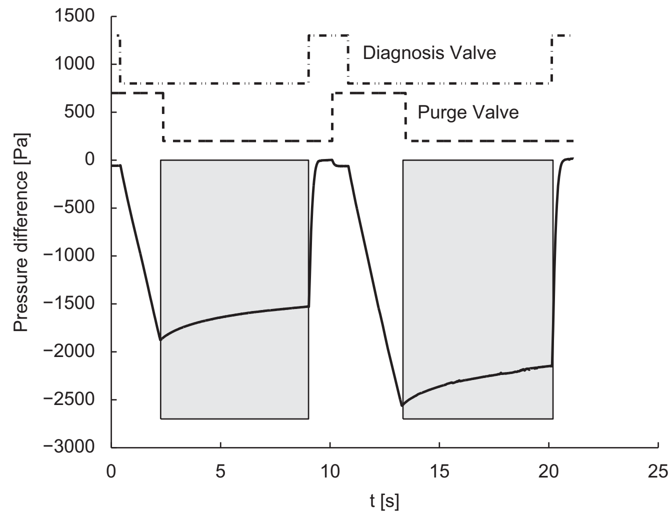

Fig. 2. Typical cycles for leakage detection for the fault-free case. The solid line is the pressure measurement and the dashed and dashed-dotted lines indicate the position of the purge and diagnosis valve. The gray areas indicate which data that are used for detecting leaks. Data are obtained from a production engine fuel system.

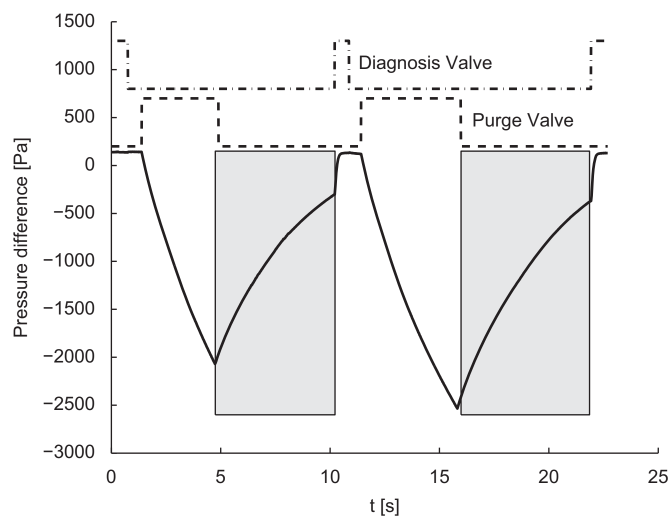

Fig. 3. Cycles for leakage detection for the case with a 1 mm leak. The solid line is the pressure measurement and the dashed and dashed-dotted lines indicate the position of the purge and diagnosis valve. The gray areas indicate which data that are used for detecting leaks.

2. System description and operation

This section will describe typical operation of the evaporative emissions control system. In normal operation, the diagnosis valve is open and the purge valve is closed. This means that evaporating fuel will be collected in the carbon canister which can be purged by opening the purge valve. To initiate a leakage detection sequence, the diagnosis valve is closed and the purge valve is opened. This results in a pressure drop in the tank which can be seen at $t = 0.5$ and 11 in Fig. 2. After about 2 s, the purge valve is closed and the tank system is, in a fault-free case, now sealed. The basic idea is now to monitor the pressure signal behavior in the shaded intervals in Fig. 2 to detect a possible leakage. In case of a leakage in the tank, the pressure will increase since air will leak into the tank from ambient air. Pressure signal behavior in case of a 1 mm leak is shown in Fig. 3. A main complication is the effect of evaporating fuel. The effects can be seen in Fig. 3 where it is clear that even though there is no leakage in the tank, the tank pressure increases. This means that a leakage with small orifice diameters produces pressure traces similar to the no-leakage case. This similarity increases with decreasing leakage orifice diameter. In the fault-free case, the tank pressure increases until it reaches its saturation pressure and since the saturation pressure is temperature dependent there is a need for the detection algorithm to take this into account to be robust towards different temperatures. An additional complication, which also can be seen in Fig. 3, is that the pressure sensor is subjected to a slowly time-varying bias. When the diagnosis valve is open and the purge valve is closed, one can expect that the tank pressure equals ambient pressure, i.e. a sensor reading of 0. However, the pressure reading at $t = 0$ in Fig. 3 is distinctly non-zero and this also needs to be considered when designing the detection algorithm.

3. Modeling

From the discussion in the previous section, it is clear that leakage detection is performed when an underpressure in the tank has been created and both valves are closed. During a leak detection test, it is assumed that the temperature T and the volume V in the tank are constant. This is reasonable since only about 3 kPa is evacuated and the leakage test is performed in less than 10 s. In the described situation, the pressure p increases by fuel evaporation and a possible leakage only. To be able to separate pressure traces from cases with small leakages and fuel evaporation from pressure traces with only fuel evaporation, a physical model of the fuel tank pressure valid in the gray shaded intervals in Figs. 2 and 3 can be used.

Given a fixed gas volume and temperature in the tank, the ideal gas law implies that the rate of pressure change $\dot{p}$ is proportional to the sum of fuel evaporation mass flow rate W_f and the leakage mass flow W_l directed into the tank, i.e.

$$\dot{p} \sim W_f + W_l \tag{1}$$

The total pressure p in the tank is according to Dalton's law equal to the sum of the partial pressure of air p_a and the partial pressure of fuel vapor p_f, i.e.

$$p = p_a + p_f \tag{2}$$

A simple model for the fuel evaporation mass flow rate W_f is that it is proportional to the difference between the saturated fuel pressure p_f^0 and the fuel vapor partial pressure p_f, i.e.

$$W_f \sim p_f^0 - p_f \tag{3}$$

The saturation pressure is dependent on temperature and fuel composition.

To get a simple model for the air mass flow W_l into the tank through a hole with an effective leakage area of size A, inviscid and incompressible flow are assumed. The air speed v through the hole can under these assumptions be computed with Bernoulli's principle as

$$p_{\text{amb}} = p + \rho v^2/2 \tag{4}$$

where ρ is the density of air and p_{amb} the ambient pressure. Eliminating v using

$$W_l = A\rho v \tag{5}$$

gives the following relationship between the air mass flow W_l and the pressure

$$W_l = A\sqrt{2\rho(p_{\text{amb}} - p)} \tag{6}$$

Combining (1), (3), and (6) gives

$$\dot{p} = k_1(p_f^0 - p_f) + k_2\sqrt{p_{\text{amb}} - p} \tag{7}$$

where k_1 and k_2 are temperature and gas volume dependent proportionality constants. Also, the evaporation constant k_1 is dependent on fuel composition, and the leakage constant k_2 on the effective leakage area A.

As said in the previous section, the process is equipped with a sensor measuring the overpressure in the tank. The sensor is assumed to have a slowly varying bias b and the sensor equation can then be written as

$$y = p - p_{\text{amb}} + b \tag{8}$$

The bias b is assumed to be constant during a 10 s leak detection test and this is assumption is consistent with experimental data. This can also be seen in the cycles shown in Figs. 2 and 3. Assuming also that the ambient pressure p_{amb} is constant, i.e. $\dot{b} = 0$ and $\dot{p}_{\text{amb}} = 0$, elimination of p and p_f in Eqs. (2), (7), and (8) results in the first order model

$$\dot{y} = -k_1 y + k_2\sqrt{b - y} + k_1(p_f^0 + p_a - p_{\text{amb}} + b) \tag{9}$$

During a test, it is assumed that sensor bias b, ambient pressure p_{amb}, temperature, gas volume, fuel composition, and leakage area are constant parameters. This means that b, p_{amb}, k_1, k_2, b, and p_f^0 are constants. However, the partial pressure of air p_a is constant only if there is no leakage and this will be considered in the leakage detection method that will be proposed in the next section.

In addition to (9), it is assumed that the modeling also includes, given a specific fuel composition, a map of parameter $k_1(V,T)$ relating fuel evaporation rate with the temperature T and gas volume V in the tank. This map can be used to compute fuel evaporation, since the temperature T can be estimated with the ambient temperature which is measured in a production engine setup. Further, the gas volume V in the tank can be computed using a fuel level sensor. An alternative to use the map $k_1(V,T)$ is to estimate k_1 immediately before each leak test by using a vapor generation test as proposed in Majkowski and Simpson (2002).

4. Leakage monitoring method

This section will describe how a leakage detection test can be designed using model (9) and careful usage of measurement data.

As noted in Section 2, the pressure sensor used suffers from a slowly varying bias that is assumed constant during the test interval. Now, note that when the diagnosis valve is open and the purge valve is closed, the tank pressure should quickly stabilize around the ambient pressure. This means that the measurement signal y should be 0 if there is no bias. Thus, the current bias can easily be estimated by taking the mean value over data where the diagnosis valve is open and the purge valve is closed. For example, from the first second in Fig. 3 it is clear that there exists a bias ≈ 150 Pa. The estimated bias can be subtracted from the measurement signal which then can be assumed to be bias free.

The portion of the test cycle that will be used for detection of leakages is, as mentioned in Section 2, the section when air has been evacuated and the purge valve has been closed. The remaining discussion in this section only applies to this portion unless otherwise stated. Model (9) is a continuous-time description of the pressure signal. Since the collected data are sampled, the detection algorithm needs a model in time-discrete form. Here, a simple Euler forward is used with sampling period T_s which results in the equation

$$y_{t+1} = (1 - T_s k_1)y_t + T_s k_2\sqrt{-y_t} + T_s k_1(p_f^0 + p_a - p_{amb}) + \varepsilon_t \tag{10}$$

The stochastic noise sequence ε_t is introduced to represent model uncertainty and measurement noise. Here, it is assumed that ε_t is a white, zero mean Gaussian sequence with unknown variance. This statistical assumption will be validated on measured data in Section 4.3.

4.1. Test quantity design

The basic objective of the detection algorithm is to alarm when the model for fault-free operation is inconsistent with the observations. Desirable properties of an algorithm are to be robust against temperature variations, pressure sensor bias, and model uncertainties. The test quantity will be based on a least-squares estimation procedure in a linear regression. As stated in Section 3, a map of parameter $k_1(V,T)$ related to fuel evaporation is available. Let $\alpha = (1 - T_s k_1(V,T))$ and matrices

$$Y = \begin{pmatrix} y_2 - \alpha y_1 \\ \vdots \\ y_N - \alpha y_{N-1} \end{pmatrix}, \quad E = \begin{pmatrix} \varepsilon_1 \\ \vdots \\ \varepsilon_{N-1} \end{pmatrix}, \quad \Phi = \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix}$$

By collecting all data, $y_1, \ldots, y_N$, from the specified portion of the test cycle, the model (10) can then, for the no-leakage case where $k_2 = 0$, be written as

$$Y = \Phi\theta + E \tag{11}$$

where $\theta = T_s k_1(p_f^0 + p_a - p_{amb})$. Note that in a no-leakage case the tank is completely sealed and therefore the partial air pressure p_a is constant but unknown. This means that θ in (11) is constant. Important to remember is that this θ is *not* constant in case of a leakage since then p_a increases when air flows into the tank.

A residual can then be computed by a maximum-likelihood estimation of the parameter θ, under a no-leakage assumption, and computing a residual

$$\hat{\theta} = \arg\min_{\theta} \|Y - \Phi\theta\|_2 = (\Phi^T\Phi)^{-1}\Phi^T Y \tag{12a}$$

$$R = Y - \Phi\hat{\theta} = (I - \Phi(\Phi^T\Phi)^{-1}\Phi^T)Y \tag{12b}$$

A test quantity can then be computed as

$$T = \frac{1}{\sigma^2} R^T R = \sum_{t=2}^{N} \frac{1}{\sigma^2} r_t^2 \tag{13}$$

where σ^2 is the variance of the residual. Note that it is straightforward to modify expressions (12) to handle the case where the noise ε_i is a non-white sequence, i.e. when $\text{cov}\{E\}$ is non-diagonal.

To compute T according to (13), the unknown standard deviation σ has to be determined. One way to estimate σ is to use the covariance of the residual. Residual (12) could be used to estimate the residual covariance in case there is no leakage. However, model (11) is not valid in case of a leakage and the resulting variance estimate then typically becomes significantly too high which would make probability of detection of a leakage unnecessary low. A more suitable way is to use the entire model (10) that is valid also for the leakage case, to estimate σ. Model (10) can then be put on the linear regression form

$$Y_2 = \begin{pmatrix} y_2 \\ \vdots \\ y_N \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} y_1 & \sqrt{-y_1} & 1 \\ \vdots & \vdots & \vdots \\ y_{N-1} & \sqrt{-y_{N-1}} & 1 \end{pmatrix} \tag{14}$$

with

$$\theta = \begin{pmatrix} (1 - T_s k_1) \\ T_s k_2 \\ T_s k_1(p_f^0 + p_a - p_{amb}) \end{pmatrix} \tag{15}$$

The maximum-likelihood estimation of θ according to (12) gives a residual

$$r_t = y_t - (y_{t-1} \quad \sqrt{-y_{t-1}} \quad 1)\hat{\theta} \tag{16}$$

and the estimate of σ can be obtained from the covariance estimation of the sequence r_t. Note that θ in (15) is *not* constant when there is a leakage since p_a then increases. However, the main objective is to get an accurate variance estimate for the no-leakage case and to not get a too high estimate of the variance in case of a leakage. This to ensure that the detectability is not lost in (13) due to a too high σ estimate.

4.2. Threshold selection

In the no-leakage case, the test quantity T in (13) is χ^2 distributed with $N-1$ degrees of freedom if σ is considered to be known. Since σ is also estimated from data, a lower degree of freedom is expected. However, the degrees of freedom is not $N-2$ since σ is estimated with the extended model given by Eqs. (14) and (15) which is not the same estimation model used to compute the test quantity. The threshold is selected such that a given false-alarm probability P_{fa} is not exceeded. Determining the threshold with $\chi^2(N-1)$ distribution table gives a conservative threshold which then guarantees that the false-alarm requirement is fulfilled. Thus, the threshold is computed as

$$J = F_{\chi^2}^{-1}(1 - P_{fa}) \tag{17}$$

where F_{χ^2} is the cumulative χ^2 distribution with $N-1$ degrees of freedom. Note that, since the threshold depends on the number of data, a predefined threshold cannot be used but must be determined on-line.

4.3. Validation of statistical assumptions

The test quantity T in (13) is χ^2 distributed under the statistical assumption that residual (12) is a white Gaussian sequence when there is no leakage in the system. To verify this assumption, fault-free data are collected from the real system and a normality plot and a covariance function estimate is computed. Fig. 4 shows that the Gaussian assumption for the residual seems reasonable, at least up to 1 standard deviation. Fig. 5 shows a covariance function estimate for the residual where also the whiteness property is corroborated.

4.4. Method summary and discussion

The leakage detection algorithm described in this section is designed to have few tunable parameters for easy design and at the same time being robust enough to work satisfactory in different operating conditions. The algorithm is first summarized and then properties of the algorithm are discussed.

1. Obtain a bias estimation for data where the diagnosis valve is open and the purge valve is closed and compensate measured data accordingly.

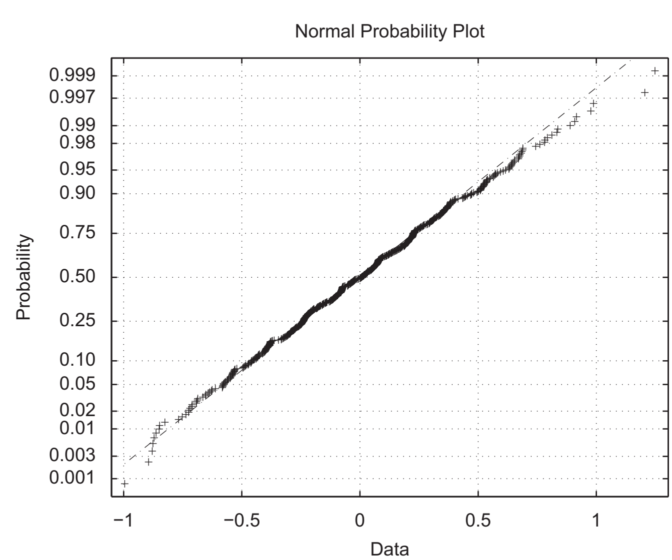

Fig. 4. Normality plot. If data are perfectly Gaussian, the plot will be linear.

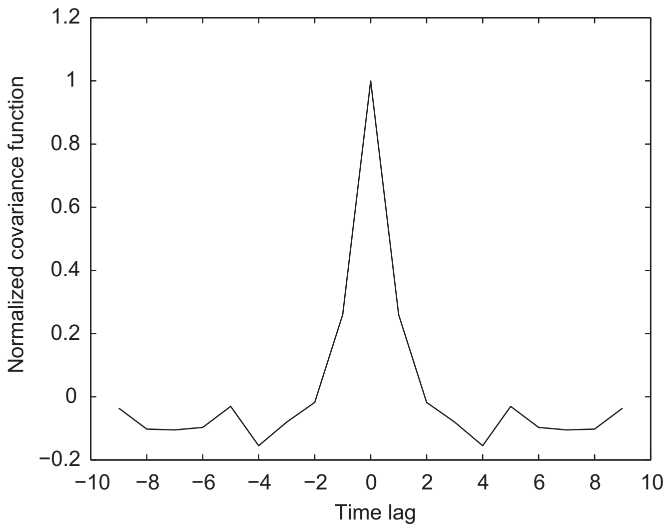

Fig. 5. Estimated covariance function. For a perfect white sequence, the covariance function is a Dirac function.

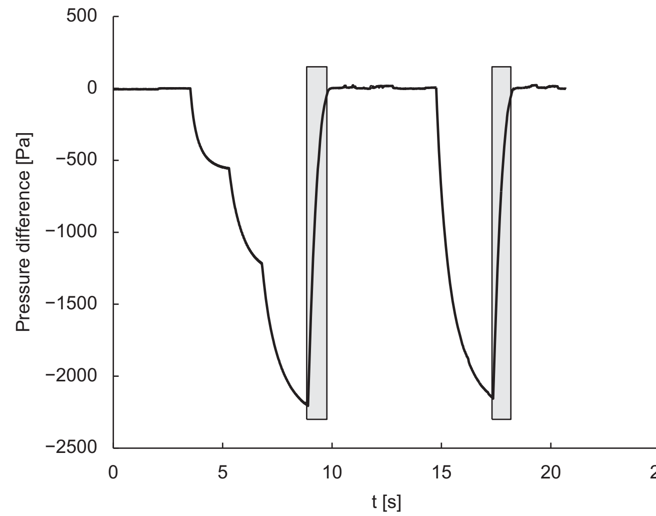

Fig. 6. Cycles for leakage detection for the case with a 3.5 mm leak. The gray areas indicate which data that are used for detecting leaks.

2. Take a set of data where the diagnosis valve is closed, air has been evacuated from the tank, and the purge valve is closed.
3. Estimate the noise variance σ^2 using (16).
4. Compute a test quantity T according to (13).
5. Determine a threshold using a predefined false-alarm rate and a $\chi^2(N-1)$ distribution table as in (17).

The approach has mainly two tuning parameters, selection of the data sets from the detection cycle in steps 1 and 2, and selection of the false-alarm probability P_{fa} used to compute the threshold in step 5.

A brief discussion now follows on four robustness properties of the algorithm: robustness against sensor gain faults, disturbances, poor excitation, and data interval selection.

First, the pressure sensor may be subject to a constant gain fault. In model (10), the noise ε_t represent model uncertainty which then is not influenced by any fault in the sensor. The test quantity will not be sensitive to such gain fault in the no-leakage case. This can be seen by observing that, in the no-leakage case, Eq. (9), corresponds to

$$\dot{y} = -k_1 y + C$$

where C is an unknown constant estimated in the detection procedure. Thus, a gain fault in the sensor reading y will cancel out and be included in the unknown constant C. However, the test quantity will be proportional to the gain in the leakage case. This means that such gain faults will not cause false alarms, but a reduction in the gain will cause a reduced detection performance.

Second, a typical disturbance is a sudden acceleration of the vehicle which causes increased vapor generation in the fuel tank as fuel sloshes in response to the sudden acceleration (Schumacher, Lynch, & Remboski, 1999). This increase of fuel vaporization might falsely be interpreted as a leakage. In Schumacher et al. (1999) this is avoided by using an algorithm for computing when a test result is valid based on wheel acceleration, fuel tank pressure, and vehicular acceleration during the test. With the proposed method no such algorithm and acceleration measurements are needed, since a sudden increase in the fuel vaporization rate implies a larger noise estimate and thereby a smaller test quantity. Pressure disturbances, caused by for example door closing, are also handled by using the noise variance estimation proposed in (16). If acceleration measurements were available, these could directly be used to improve also the approach proposed here.

Third, since the procedure involves a parameter estimation step, poor level of excitation is often an issue. In this problem setting, the level of excitation primarily depends on the level of evacuation. However, since the approach directly uses residual (12), the test quantity will be small as long as the fault-free model can, for any value of θ, describe the observed data. Generally, a larger evacuation results in better detection performance but cases with poor level of excitation will be automatically handled and thresholds will be adjusted accordingly.

The fourth and final issue discussed is the data interval selection. The number of available data in a selected interval varies with situation, compare for example Figs. 2 and 6. It is therefore not possible to use a predefined threshold for all leakage checks and the threshold in step 5 is dependent on the number of samples used in the test. The starting point of the interval is preferably chosen some predefined time after closing of all valves. It is not suitable to start collecting data immediately since unmodeled pressure phenomena occur immediately after valve closing. The length of the data interval is chosen as long as possible, the more data the better detection performance.

When comparing the proposed approach to other published vacuum-decay based works it is noteworthy that many works, for example Majkowski and Simpson (2002) and Perry and Delaire (1998), propose methods that are based on linear pressure development. Typically, the time needed for the pressure to rise a predefined amount is used to indicate possible presence of a leak. However, when observing measured data, for example in Fig. 2, it is clear that the pressure development is far from linear and exhibits evident exponential behavior. Thus, to use such an approach would require careful tuning of data intervals. Possibly, the use of pressure regulators (Perry & Delaire, 1998) can be used to stabilize the pressure in the tank before leakage checks, to increase stability of detection performance and avoid false alarms. The proposed model based approach is not as sensitive to, for example, data interval selection. This is because the key step is the parameter estimation step which is done based on all data points in the selected interval. Thus, single outliers or small disturbances do not have a major effect on the proposed test quantity.

5. Experimental evaluation

This section gives a brief evaluation of the proposed approach on measured data collected from a fuel tank, connected to a standard production engine in a laboratory environment. Only standard production sensors are used in the measurements. Leakage orifices, ranging from 0.5 to 5 mm in diameter, have been artificially imposed on the tank system by drilling holes in bolts that are fastened in the fuel tank. This makes it possible to evaluate detection performance in the real system. To evaluate detection performance, the test quantity is plotted as a function of leakage size. The false-alarm probability, used in the threshold selection, is set to 1% in this evaluation.

One problem with evaluating the performance is that different test cases have different amounts of data which further means that it is not possible to use the same threshold for all test quantities. Thus, to evaluate the performance a normalized test quantity is computed where T_i in (13) is divided with the corresponding threshold J_i from (17), i.e.

$$T_{i,norm} = \frac{1}{J_i} T_i = \frac{1}{J_i \sigma^2} R_i^T R_i$$

Fig. 7 shows the detection performance plotted against leakage diameter. The gray area indicates the region for test quantities based on a number of measured test cycles. Note that the plot is in logarithmic scale which, for example, means that the median value of the test quantity for 1 mm leakage is about 3 times the threshold. This performance is achieved with data lengths ranging from 10 down to 1 s for 5 mm leakages.

It is important that small leakages are reliably detected and to illustrate performance, Fig. 8 shows the performance of the approach for 0.5 mm leakages. In each test, the purge valve is opened until a 2.5 kPa under-pressure is created. The leakage test is started approximately 3 s after the purge valve has been closed. This delay is introduced to avoid pressure disturbances caused by the closure of the purge valve. Then 4 s of data is used for detecting leaks. The figure shows that there is a significant

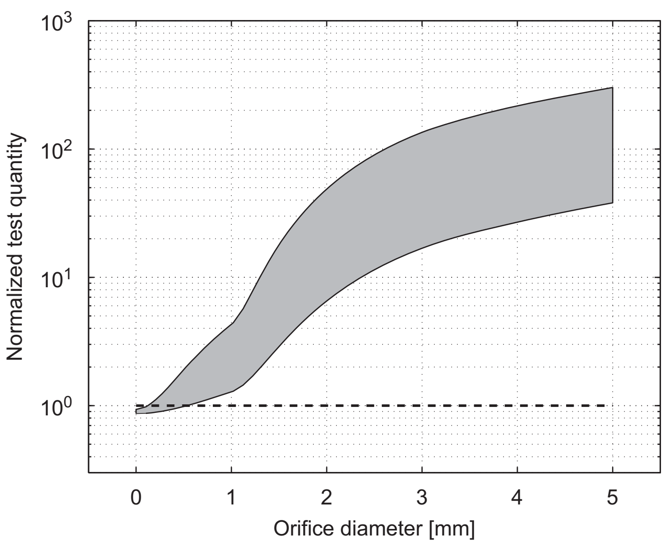

Fig. 7. Detection performance for different leakage sizes. The dotted line is the threshold for the normalized test quantity. Note that the normalized test quantity is plotted in logarithmic scale.

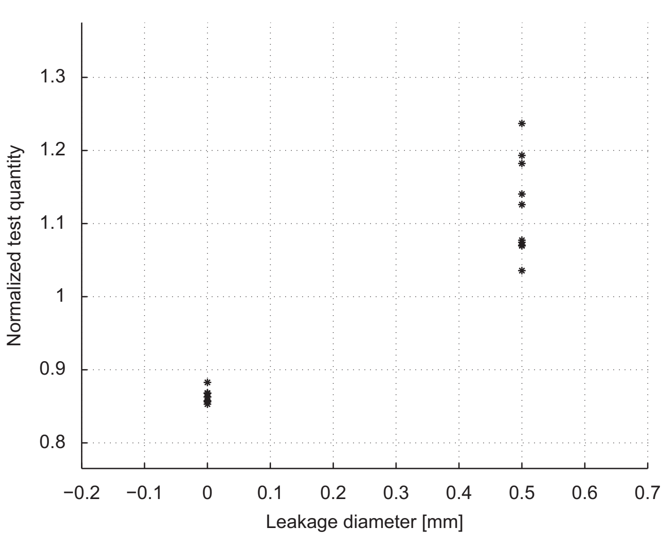

Fig. 8. Detailed analysis of 0.5 mm leakages. This performance is achieved with data lengths of 4 s.

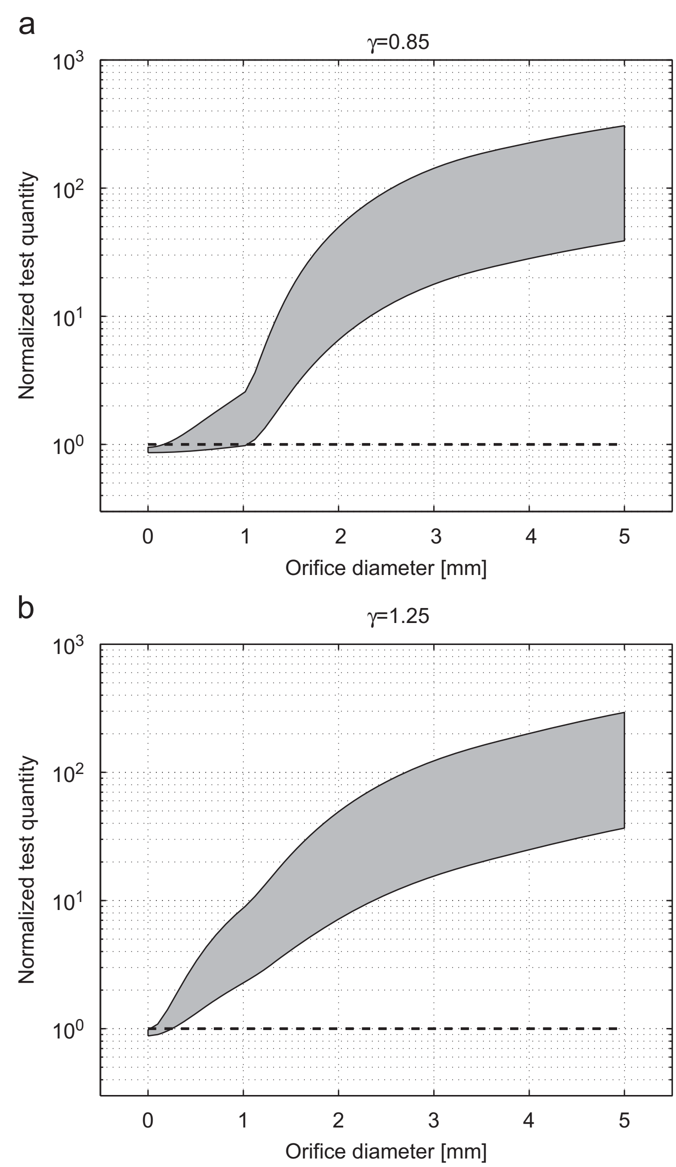

Fig. 9. Performance evaluation of robustness against inaccuracies in the k_1-map. (a) 15% underestimation of k_1, i.e. $\gamma = 0.85$ (b) 25% overestimation of k_1, i.e. $\gamma = 1.25$.

separation between faulty and non-faulty test cases also for small leakages which makes detection reliable. It is worth noting that a good separation is achieved with only 4 s of data, while the two approaches presented in Andersson and Frisk (2001) require more than 20 s of data to achieve comparable results.

5.1. Robustness against inaccuracies in the k_1-map

The proposed approach assumes that a map $k_1(V,T)$ of the evaporation constant is available. Since it is, in general, difficult to obtain a map of the evaporation constant that is accurate in the entire operating range, this section evaluates the effect of inaccuracies in the k_1 map. In the experimental evaluation above, producing Fig. 7, a constant k_1 estimated from data measured on a leakage free tank is used. To evaluate the robustness properties, the estimated k_1 used above is replaced by γk_1 where the parameter γ is varied in the range from $\gamma = 0.85$ to 1.25, i.e. from a 15% underestimation of k_1 to a 25% overestimation.

The detection performances for the two extremal cases are shown in Fig. 9 which should be compared to Fig. 7. One conclusion of these experiments is that even for rather large deviations in the k_1 map, the approach performs well and deviations in k_1 introduce a gentle deterioration of detection performance. The experiments also indicate that it is better to overestimate the evaporation constant than to underestimate since, with an overestimated k_1 one can note a slight increase in false-alarm probability while keeping the detection performance. With an underestimated k_1, the false-alarm probability is hardly affected but the detection performance for small leakages may decrease.

6. Conclusions

Leakage detection in a vacuum-decay based fuel evaporative system for automotive vehicles has been considered. The objective has been to develop an easily tuned and systematic detection algorithm that detects small leakages under different operating conditions.

The proposed solution is based around a first principles physical model of the pressure signal that is supplied by the pressure sensor mounted in the fuel tank. By careful statistical analysis of the model and real data together with statistical maximum-likelihood estimation methods, a leakage detection algorithm has been developed. It is worth noting that the model is incomplete in the sense that the dynamics of the partial air pressure in the tank is not described by the model equations. However, careful use of the model still makes it possible to fully utilize the model equations. The tuning of detection thresholds is done by selecting a given false-alarm probability.

Since different levels of excitation, pressure disturbances, and sudden increases of the fuel evaporation rate are automatically handled in the algorithm, it means that no complicated logic is needed to decide if acceptable conditions to run the test are met and this results in an algorithm with few and easily tuned variables.

The algorithm successfully detects small leakages using small amounts of data, typically less than 10 s. For different sizes of leakages, the amount of useful data varies significantly, from about 5 s for a 1 mm leak to less than a second for a 3.5 mm leak. This variation need to be considered in the algorithm, for example when selecting thresholds and this is done automatically in the approach. The approach is fast, requires no expensive additional hardware and has been successfully evaluated on a production engine and fuel system setup in a laboratory environment. The approach is model based and the main model constant is an evaporation related constant k_1. It has been validated on experimental data that the algorithm is robust against parameter uncertainties in k_1.

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