Institutionen för systemteknik
Department of Electrical Engineering

Examensarbete

Diagnosis of a compressed air system in a heavy vehicle

Examensarbete utfört i Fordonssystem
vid Tekniska högskolan vid Linköpings universitet
av

Martin Kågebjer

LiTH-ISY-EX--11/4500--SE

Linköping 2011

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Titel
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Diagnos av tryckluftssystem i ett tungt fordon
Diagnosis of a compressed air system in a heavy vehicle

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Sammanfattning
Abstract

Compressed air has in the past been considered as a free resource in heavy vehicles. The recent years work to minimize fuel consumption has however made air consumption an interesting topic for the manufactures to investigate further.

Compressed air has many different applications in heavy vehicles. One important consumer of compressed air is the brake system, which would not work at all without compressed air. The compressed air is produced by a compressor attached to the engine. A leakage in the system will force the compressor to work longer, which leads to an increased fuel consumption.

It is of large interest to have a diagnosis system that can detect leakages, and if possible also provide information about where in the system the leakage is present. This information can then be used to repair the leakage at the next service stop.

The diagnosis system that is developed in this thesis is based on model based diagnosis and uses a recursive least mean square method to estimate the leakage area. The results from the validation show that the algorithm works well for leakages of the size 1-10 litres/minute. The innovative isolation algorithm gives full fault isolation for a five circuit system with only three pressure sensors.

Nyckelord
Keywords

Air leakage detection, Parameter estimation, System modelling

Abstract

Compressed air has in the past been considered as a free resource in heavy vehicles. The recent years work to minimize fuel consumption has however made air consumption an interesting topic for the manufactures to investigate further.

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Sammanfattning

Tryckluft i lastbilar har tidigare ansetts vara en fri resurs. Den senaste tidens försök att minimera bränsleförbrukningen har dock lett fram till att även användandet av tryckluft har börjat ses över.

Tryckluft används i dagens lastbilar av flera olika förbrukare. En viktig förbrukare av tryckluft är bromsarna som inte fungerar överhuvudtaget utan tryckluft. Tryckluften produceras av en kompressor som sitter kopplad på förbränningsmotorn. Om det finns ett läckage i tryckluftsystemet leder detta till att kompressorn måste arbeta oftare vilket i sin tur leder till en ökad bränsleförbrukning.

Det finns stort intresse av att kunna detektera dessa läckage och om möjligt även avgöra var i systemet som läckaget finns. Informationen kan sedan användas vid nästa servicetillfälle för att laga läckaget.

Diagnossystemet som utvecklats i detta examensarbete bygger på modellbaserad diagnos och använder en rekursiv implementering av minstakvadratmetoden för att skatta läckagets storlek. Resultat från validering av algoritmen visar att diagnossystemet fungerar bra för läckage i storleksordningen 1-10 liter/minut. Den innovativa isoleringsalgoritmen ger full felisolerbarhet för ett system med fem kretsar men bara tre tryckgivare.

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Nomenclature

Symbol	Description	Unit
F	Force	N
m	Mass	kg
a	Acceleration	m/s^2
p	Pressure	pa
A	Area	m^2
$\hat{A}$	Estimated area	m^2
V	Volume	m^3
ρ	Density	kg/m^3
v	Velocity	m/s
R	Gas constant for air	J/kgK
T	Temperature	K
h	Enthalpy	J
c_p	Specific heat capacity (constant pressure)	J/kgK
c_v	Specific heat capacity (constant volume)	J/kgK
γ	Ratio of specific heats (c_p/c_v)	-
M	Mach number	-
$Ex(t)$	Expectancy of x(t)	-

Chapter 1

Introduction

Compressed air is used for a lot of different applications in heavy vehicles. The break system is one important consumer of compressed air. The engine and the after treatment system are also using compressed air and some vehicles have additional air suspension. There can be many different air circuits with varying circuit pressure. The amount of circuits depends on the requirements of the air consumers. The compressed air system is fed by a compressor attached to the engine. To avoid that the whole system is drained in case of a large leakage in one of the circuits, there are safety valves that isolate the circuits that leak. However, there are not only the leakages that risk draining the system during driving that is a problem. Smaller leakages in the system will cause the compressor to work harder than necessary, leading to increased fuel consumption. It is therefore desirable to have a diagnosis system that can detect these small leakages, and if possible also provide information about which circuit that is leaking. This information can then be used to repair the leakage at the next service stop.

1.1 Related research

In the automotive industry, leakage detection systems are common in use for detecting leakages in the fuel tank. The reason for using a diagnosis system for fuel tanks is that in the case of a hole, unhealthy fuel vapours will leave the tank. There are many different approaches for detecting leakages in fuel tanks. One example is [8] that estimates the leakage area in the fuel tank by considering pressure, temperature and flow from the fuel pump.

In the case of detecting leakages in the compressed air system the research is not as fully developed, mainly because air has been considered as free in the past. The recent years work to minimize fuel consumption has however made this topic interesting for the manufactures to investigate further. There are some reports and patents considering leakage detection in the air system. One interesting master thesis, [3], studies the possibility to use a statistical approach to detect leakages in the compressed air system during driving. The conclusion from the report is that detection with this technique is possible to use, but the occurrence of false alarms is difficult to avoid. Two patents in the field are [2] and [7].

In [2] the invention is about monitoring the pressure in the air pressure system after that the ignition has been switched off. The reason for monitoring the pressure could according to [2] be for leakage detection. Exactly how the detection should be performed is not presented.

The invention in [7] is about leakage detection in the compressed air system when the vehicle is turned off. The main idea is to monitor the pressure in order to calculate a constant, Rossi alpha, for an exponential function. The value of the constant can then be used for diagnosis.

The main differences in the solution in this thesis are that the diagnosis solution is fully based on model based diagnosis. Another difference is that the leakage area is estimated using a recursive algorithm in order to take a decision if there is a leakage or not in the system. The isolation algorithm and performance are also different from what is presented in [7]. The solution in this thesis gives full isolation performance for a five circuit system with only three pressure sensors, which is not presented in [7].

1.2 APS

The most important part in the compressed air system is the Air Processing System, APS. The APS is fed with compressed air from the compressor attached to the combustion engine. One of the most important tasks for the APS-unit is to dry and clean the air from oil and dirt. The cleaning process is made when the air passes through the air dryer, which is attached to the APS. After the air is cleaned, it is fed into different circuits. A pressure limiter ensures that the pressure in the low pressure circuits does not get too high, even if the compressor is delivering a higher pressure. The circuits not handled by the pressure limiter are directly fed from the compressor and have therefore most of the time a higher pressure then the low pressure circuits. In normal conditions, when the pressure in the system is high, all circuits are connected to each other. If the pressure in one of the circuits is decreased, air will flow to that circuit from the other circuits, compensating the pressure differences. To protect the system from being drained if a large leakage occurs the circuits are protected by safety valves. If the pressure in one of the circuits gets too low, the safety valve belonging to that circuit closes. In doing this, pressure in the rest of the system is preserved. A circuit diagram for the APS connected to four tanks is shown in Figure 1.1. The important components for the air pressure system are shown in the figure. The components that exist in the APS unit are inside the dashed line. The bypass bleeds is represented with filled blocks. For the one way bypass bleeds the flow direction is marked with arrows. The air consumers are attached to the tanks and circuits, those are not shown in the figure.

1.2.1 Different circuits

The maximum number of circuits connected to the APS is five. Three are high pressure circuits, with a maximum pressure of 12.5 bar. The other two circuits are

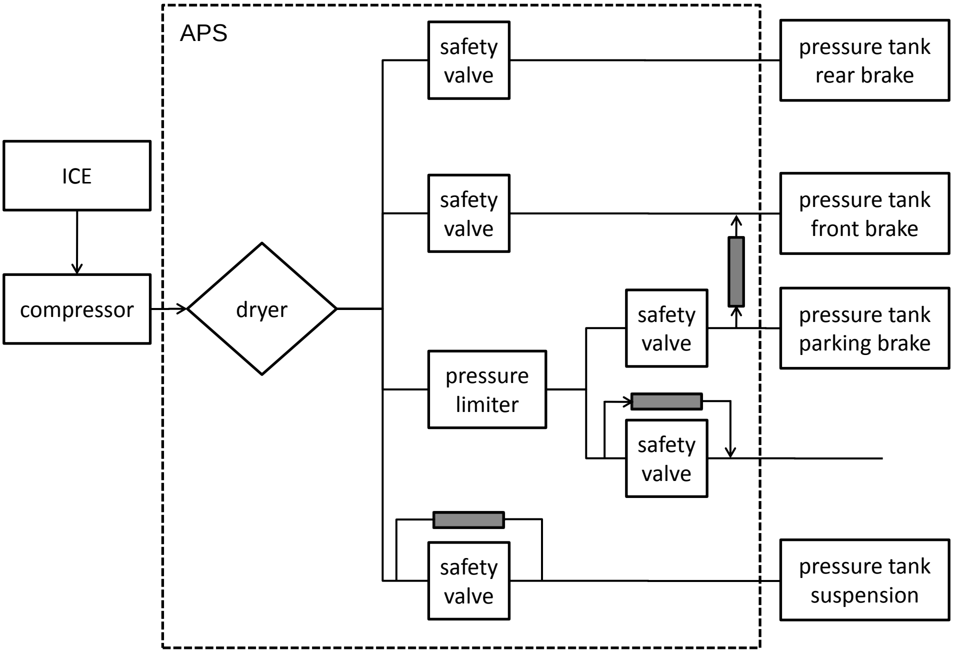

Figure 1.1. Circuit diagram for the APS with compressor, attached to the internal combustion engine, and connected pressure tanks. The filled blocks without text represents bypass bleeds and the arrows indicates the flow direction. Bypass bleeds without arrows allow air to flow in both directions. The circuit without pressure tank is the auxiliary circuit.

limited by the pressure limiter to a maximum pressure of 8.5 bar. Two of the high pressure circuits are used by the brakes, one for the front wheels and one for the rear wheels. The last high pressure circuit is used by vehicles with air suspension. The low pressure circuits are used by the parking brake and auxiliary components.

1.2.2 Flow between circuits

Air can flow between the circuits in the main ducts when the pressure is high and the safety valves are open. When the safety valves are closed no air passes through. However the air might still flow between some of the circuits. The front brake circuit is connected to the parking brake circuit with a one way bypass bleed. This bypass bleed allows a small flow from the parking brake circuit to the front brake circuit, but not the other way around. The auxiliary circuit has also a one way bypass bleed, enabling air to flow to this circuit. Only a single two way bypass bleed exists in the system. It is located over the safety valve for the air suspension circuit.

1.3 Introduction to diagnosis

The idea of diagnosis is to use knowledge and observations of a system to determine whether the system has any faults or not. How to decide if the system has any faults is the main task in diagnosis. One important part is to have knowledge of the system. The knowledge about the system can be used to determine which variables or behaviour that is important to study. By doing this, it is possible to determine if the system is working normally or not. There are many different definitions of the word diagnosis. The definition used in this thesis is the definition used in [10].

> "The diagnosis system produces diagnoses. A diagnosis is a conclusion of what fault or combinations of faults that can explain the process behavior."

1.3.1 Importance of diagnosis

There are many reasons and examples in technical applications where diagnosis is important, see [10]. One reason for this is that there are a lot of systems, where a fault that is not detected in time can give catastrophic consequences. One example of this is a nuclear power plant where a fault, e.g. in the cooling system, is very dangerous if not detected in time. Therefore, an automatic diagnosis system that supervises the process and sends an alarm if something is wrong is useful. The diagnosis can make it possible to, in this example; stop the power plant before it is too late. Diagnosis can also be important in systems where a fault is not dangerous. Here the fault may have other undesired consequences, e.g. increasing the fuel consumption or the emissions of a vehicle.

1.3.2 Diagnosis definitions

A short explanation of some important definitions is discussed briefly below, see [10] for a depletive explanation.

- **Fault**

  The main reason for a diagnosis system is to supervise a system in order to find faults. A fault is a deviation in the system that is not explained by the nominal behaviour of the system. Any change in the system characteristic property that is not normal is a fault.

- **Fault detection**

  To be able to say that a fault in the system has occurred the fault has to be detected. Fault detection is to determine if any faults are present in the system.

- **Fault isolation**

  If a fault is present in a system it can, besides detecting the fault, also be of interest to determine where in the system the fault has occurred. Consider a large pipe system with water. Knowing there is a leak, it is desirable to also know which part or where in the system the leak is. An example of fault isolation, is to say where or what component in the system that is leaking.

1.4 Problem formulation

The problem formulation in this master thesis is to study the possibility to detect small leakages in the compressed air system in a truck when the vehicle is turned off. The diagnosis system should be able to detect small leakages in the system, and also determine in which circuit the leakage has occurred. In today's system not all circuits have sensors monitoring the pressure in the system. Therefore the problem also includes studying if the performance of the diagnosis system would improve if all circuits have pressure sensors. Another task is to try to reduce the amount of data necessary and still be able to make a correct diagnosis. When the vehicle is turned off the electric energy consumption should be limited. It is therefore preferable if the diagnosis system can use a lower sample rate (e.g. only one sample taken every half hour) and still make a correct diagnosis. The goals can be listed in the following order where goal number 1 has highest priority.

1. The diagnosis system should be able to detect a small leakage in the compressed air system, at least leakages of the size that gives an air flow of 10 litres/minute when the pressure in the system is 10 bar, without giving any false alarms on systems which are not leaking.

2. The diagnosis system should be able to determine in which of the circuits the leakage is present.

3. The amount of data required should be analysed in order to make the diagnosis system more energy efficient.

4. The performance improvement for a diagnosis system with pressure sensors in all circuits, compared to only have the sensors that are existing in today's standard heavy trucks, should be analysed.

1.5 Definitions

Some definitions that need to be explained in this thesis are; best estimation, the use of the word settling time and the leakage sizes (1 litre/minute and 10 litres/minute).

1.5.1 Best estimation

In the development and validation of the diagnosis algorithm, the estimated area needs to be compared to some sort of reference, in order to get an idea of how good the result is. The implemented leakages used in this thesis are steel sockets with a small drilled hole. The exact size of the hole is difficult to measure accurately.

Therefore the mean value of the estimated area from all measurements for a specific implemented leakage is calculated, this value is called best estimation. In the validation of the algorithm it will be the same steel sockets that are used. The best estimation will be the reference value for the validation. If the value in the validation is close to the mean value of the other estimations this indicates that the diagnosis algorithm gives reliable results.

1.5.2 Settling time

Since the leakage area is estimated with a recursive filter there is a design parameter, μ, that needs to be tuned. The use of the word settling time will refer to how long time that is needed for the filter to reach a representative value for the leakage area. The filter is always initialized to zero, assuming there is no leakage, and therefore there is always a settling time in the estimation.

1.5.3 Leakage size

Two common leakage sizes in this thesis occur often, 1 litre/minute and 10 litres/minute. The leakage size can also be expressed in effective leakage area. The expression x litre/minute is a calculated air mass flow for a specific area when the pressure in the tank is 10 bar. The leakage area that gives a flow of 1 litre/minute is $8.5 \cdot 10^{-9}$ m^2 and 10 litre/minute is given by a leakage area of $8.5 \cdot 10^{-8}$ m^2, when the pressure in the leaking tank is 10 bar.

1.6 Thesis outline

This section gives a short summary of the main topics presented in this thesis.

- **Chapter 2: Theory**

  The theory chapter presents important theory that is used when solving the problem listed in Section 1.4. The theory that is presented is concerning both fluid mechanics and diagnosis.

  To be able to build a physical model of the air pressure system and the influence that a leakage has on the system, some well known equations from fluid mechanics are needed. The equations that are used in this thesis are presented and derived in this section. The theory includes both compressible and incompressible flow.

  The diagnosis algorithm that is developed in this thesis is based on model based diagnosis. In Section 2.2 the fundamentals of model based diagnosis and how parameter estimation can be used for diagnosis is presented. The CUSUM algorithm is also presented since it can be used together with the parameter estimation when deciding if there is a leakage in the system or not.

- **Chapter 3: Modelling**

The modelling chapter presents the physical models that are used in this thesis. The modelling is done using the theory that is presented in the theory chapter. To model the APS, incompressible flow is assumed, since the pressure differences in the system are assumed to be small. The pressure drop model that describes how the pressure in the system is decreased because of the existence of a leakage is done using compressible flow theory. The modelling section also includes how temperature changes affect the pressure in the system.

- **Chapter 4: Diagnosis algorithm**

  The diagnosis algorithm chapter presents the diagnosis strategies that are analysed in this thesis. The way of how to implement the theory is presented and results are presented with figures and values. Parameter estimation is the main part of the chapter and how the accuracy of the estimations can be improved by using a temperature compensating model and the CUSUM algorithm. The isolation strategy and performance are also presented.

- **Chapter 5: Validation**

  In the validation chapter the diagnosis algorithm performance is discussed and presented. The final validation is done with collected data that has not been used during the development of the algorithm.

- **Chapter 6: Conclusions**

  In the conclusions chapter the results from the validation are discussed and a recommended solution is presented. Some future work is also presented.

Chapter 2

Theory

In order to model the system and to create a good diagnosis system, some theoretical known facts are needed. Some fluid mechanics theory and some important diagnosis fundamentals are presented.

2.1 Fluid mechanics

Some theoretical equations are necessary to be able to construct a model of the air pressure system. There are two different ways to model the internal flow between circuits. The flow can either be compressible or incompressible. The difference is that in compressible flow the change in density is considered which not the case is in incompressible flow, where the density is considered constant, see [1].

2.1.1 Incompressible flow

As mentioned before the density will be considered constant when deriving the equations for incompressible flow. One important equation for incompressible flow is the Bernoulli equation, the derivation is presented below but can also be found in [1]. The equation can be derived from Newton's second law

$$\sum F = ma.$$

A common way of thinking when dealing with fluids is to use a control volume. A control volume is a fixed volume in space through which fluid flows, e.g. a section of a pipe. In steady state the mass of the fluid in the control volume can be considered constant. If the pressure in one end of the control volume is p and the cross section area for a stream line is dA, the force acting on that point is pdA. Assuming there is a different pressure in the other end of the control volume, $p + dP$, the force in that point is $(p + dp)dA$. The total force acting on the control volume is therefore

$$F = pdA - (p + dp)dA.$$

The right hand side of Newton's law can be written as

$$ma = m\frac{dv}{dt} = m\frac{dv}{dx}\frac{dx}{dt} = mv\frac{dv}{dx}.$$

Rearranging the equations gives

$$-dp\ dA = \ \rho\ dA\ dx\ v\frac{dv}{dx}.$$

Eliminating dA, simplifying and using the fact that $vdv = \frac{1}{2}dv^2$ gives

$$-\frac{dp}{\rho} = \frac{dv^2}{2}.$$

Integration on both sides finally gives the Bernoulli equation, note that the force of gravity has been neglected in the calculations,

$$\frac{P}{\rho} + \frac{v^2}{2} = \text{constant}.$$

If the equation is applied between two points in a pipe, p_1 and p_2, where the velocity is zero in one of the points the velocity at the other point can be calculated with

$$v = \sqrt{\frac{2(p_1 - p_2)}{\rho}}.$$

The mass flow in the pipe is then given by

$$\dot{m} = A\rho v = A\rho\sqrt{\frac{2(p_1 - p_2)}{\rho}}. \tag{2.1}$$

The ideal gas law can be used to calculate ρ,

$$pV = mRT \Leftrightarrow \rho = \frac{m}{V} = \frac{p}{RT}. \tag{2.2}$$

Substituting ρ in (2.1) using (2.2) gives the final expression

$$\dot{m} = A\sqrt{\frac{2p\Delta p}{RT}}. \tag{2.3}$$

A is the effective flow area and might be unknown. In those cases the area can be estimated by using the least square method.

2.1.2 Compressible flow

The effects of compressibility must be considered when the pressure difference between two points in a flow is large. To make these calculations manageable, the flow is assumed to be isentropic (the entropy of the system remains constant, see [6]). The assumptions for isentropic flow are: no heat is added to the flow and no frictions or dissipative effects exist. A full derivation and examples are given in [5]. The first law of thermodynamics states that

$$h_0 = h + \frac{v^2}{2}.$$

Together with some equations for a perfect gas:

$$\delta h = c_p \delta T,$$

$$c_p - c_v = R,$$
$$\frac{c_p}{c_v} = \gamma,$$
$$c_p = \frac{\gamma}{\gamma - 1} R,$$

this gives an expression for the flow velocity

$$v = \sqrt{\frac{2\gamma}{\gamma - 1} R(T_0 - T)}. \tag{2.4}$$

Rearranging (2.4) results in

$$\frac{T_0}{T} = 1 + \frac{v^2}{2c_p T} = 1 + \frac{v^2}{\gamma R T}\frac{\gamma R}{2c_p}. \tag{2.5}$$

Combining (2.5), the fact that the speed of sound for a perfect gas is $c = \sqrt{\gamma R T}$, and the definition of macnumber $M = \frac{v}{c}$, gives an important relationship for temperatures at two points in the flow

$$\frac{T_0}{T} = 1 + \frac{\gamma - 1}{2} M^2. \tag{2.6}$$

The mass flow is as mentioned before given by

$$\dot{m} = A\rho V. \tag{2.7}$$

By applying the perfect gas law on (2.7), doing some extensions and using (2.6) finally gives

$$\begin{aligned} \dot{m} &= A\rho V = A\frac{p}{RT}V = \frac{pV}{\sqrt{\gamma R T}}\sqrt{\frac{\gamma}{R}}\sqrt{\frac{T_0}{T}}\frac{1}{\sqrt{T_0}} \\ &= A\sqrt{\frac{\gamma}{R}}\frac{p}{\sqrt{T_0}} M \sqrt{1 + \frac{\gamma - 1}{2} M^2}. \end{aligned} \tag{2.8}$$

This equation relates the mass flow to the pressure, temperature at the high pressure side, area and the mach number. The static pressure p is relating to a point in the flow e.g. in a tube where the mach number at that specific point is M. In order to get an effective equation to calculate the flow e.g. out of a high pressure tank, the pressure p is preferably eliminated. To do this, the flow is assumed to be isentropic. The relation between temperature and pressure for an isentropic process of a perfect gas is

$$\frac{T}{T_0} = \left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}}. \tag{2.9}$$

This equation together with (2.6) gives the relation between pressure ratio and M,

$$\frac{p_0}{p} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{\gamma}{\gamma-1}}. \tag{2.10}$$

If p in (2.8) is eliminated using (2.10) and if the area is known the mass flow can be calculated using only M and the stagnation pressure and temperature,

$$\dot{m} = A\sqrt{\frac{\gamma}{R}}\frac{p_0}{\sqrt{T_0}}\frac{M}{(1+\frac{\gamma-1}{2}M^2)^{\frac{\gamma+1}{2(\gamma-1)}}}.$$

The speed of the flow will approach mach number = 1 when the pressure difference is high. When $M = 1$ the mass flow is maximal. Under these circumstances the flow rate is only depending on the stagnation temperature and pressure,

$$\dot{m}_{max} = A\sqrt{\frac{\gamma}{R}}\frac{p_0}{\sqrt{T_0}}\left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}}. \tag{2.11}$$

To determine if the flow is choked (2.9) can be rearranged and letting $M = 1$. If the pressure ratio is larger than the expression on the right hand side the flow is choked

$$\frac{p}{p_0} \geq \left(1 + \frac{\gamma-1}{2}\right)^{\frac{\gamma}{\gamma-1}}.$$

2.2 Diagnosis

The diagnosis approach that is used in this thesis is model based diagnosis. Parameter estimation is one way to use a model of the system in order to estimate an unknown parameter.

2.2.1 Model based diagnosis

A model for the system is needed to use model based diagnosis, see [10] for more information of model based diagnosis. The model does not only have to explain the system behaviour when no faults are present but also how the system reacts to different faults. If a model exists for a system and it is possible to do observations of that system, the observations together with the model can be used for diagnosis. If the observations differ from the expected behaviour, given by the model, a fault might have occurred. Consider the example where the model is

$$\dot{x} = -cx. \tag{2.12}$$

If there is a sensor y, measuring the quantity x, with the relation $y = x$, then (2.12) can be rearranged to

$$\dot{y} + cy = 0. \tag{2.13}$$

This is called a consistency relation. In the fault free case the equation will be satisfied. If not, this indicates that something is wrong, either in the system or in the sensor. In reality there are no perfect models and there will be measurement noise for the sensor which has to be considered. However, if the model and also the sensor are good and the consistency relation is not fulfilled, this strongly indicates a fault.

2.2.2 Parameter estimation

One way to create a residual is to use parameter estimation, see [10]. The parameter estimation approach can be used when the model has an unknown parameter whose value can be used for diagnosis. If (2.13) is used, and the constant c is unknown, the parameter c can be estimated with parameter estimation. The parameter can for example always be lower than a known value in the fault free case and larger in the faulty case. By estimating the value of the parameter and comparing the estimated value with the known maximum value in the fault free case, a decision can be made whether a fault exist in the system or not.

Estimation algorithm

The Least Mean Square, LMS, algorithm can be used for parameter estimation, see [4]. If the model is written in the form

$$y(t) = \varphi(t)^T \theta$$

where φ is known and y(t) are the measurements. The model error can then be expressed by

$$V(\theta) = \frac{1}{2} E \left(y(t) - \varphi^T(t)\theta \right)^2$$

where E is the expectation value. The negative gradient of $V(\theta)$ with respect to θ is

$$-\frac{d}{dt} V(\theta) = E\varphi \left(y(t) - \varphi^T \theta \right).$$

If the value of the estimated parameter is continuously updated, the negative gradient gives information about how to update the value of the parameter. The continuous algorithm is then given by

$$\hat{\theta}(t) = \hat{\theta}(t-1) + \mu\varphi(t) \left(y(t) - \varphi^T \hat{\theta}(t-1) \right). \tag{2.14}$$

The design parameter μ is chosen to give a desired settling time in relation to noise level for the estimation. A small μ gives long settling time but reduces noise in the estimation better than a larger μ that gives shorter settling time.

2.2.3 CUSUM Algorithm

The CUSUM, Cumulative SUM, algorithm is a simple non linear detection algorithm. CUSUM can be used on a residual that contains a lot of noise, where it otherwise could be hard to choose a threshold. A too low threshold makes the noise exceed the threshold and a higher threshold might result in missed detection. The full analytical derivation of the CUSUM algorithm can be found in [10]. The CUSUM algorithm was first proposed in [11]. If the algorithm is applied to a signal $s(t)$, that has the properties

$$\begin{array}{ll} Es(t) < 0, & \text{in a fault free situation and} \\ Es(t) > 0, & \text{when a fault has occurred.} \end{array}$$

A test quantity $T(t)$ can be implemented as

$$T(t) = max(0, T(t-1) + s(t) - \nu), \tag{2.15}$$

where $T(t)$ will be small as long as the mean of $s(t)$ is less than ν. If the mean of $s(t)$ is larger than ν the test quantity will increase as long as $s(t)$ is larger than ν. An alarm is generated if the test quantity becomes larger than some positive threshold. The parameter ν is a design parameter that can be used as an adaptive threshold. If the model error is larger in some operating points an increase of ν in those points might be necessary in order to decrease the risk of false alarms.

Chapter 3

Modelling

The diagnosis strategy which is used in this thesis is based on model based diagnosis. Because of the model based approach it is important to have a good model for the system. See [9] for information about modelling. In this chapter the APS with pressure circuits, and how a leak will affect the system, are modelled.

3.1 APS modelling

The internal flow in the APS and the circuits are modelled using the theory from Section 2.1.1. The reason for using incompressible flow equations is that the pressure differences in the system are small. Equations used for modelling the flow between the circuits are given by the ideal gas law and (2.3). The flow in the system can be divided into three different categories: the flow between high pressure parts and the flow between low pressure parts in the system when the safety valves are open, the flow between high and low pressure circuits over the pressure limiter valve and the flow in the small bypass bleeds. The circuit diagram for the APS is shown in Figure 1.1. The circuits handled by the pressure limiter, the auxiliary and parking brake circuit, have limited pressure even if the compressor is on and the pressure in the other circuits is higher. The maximum pressure in the low pressure circuits is 8.5 bar.

3.1.1 Estimation of model parameters

The constant A, corresponding to the effective flow area, has to be estimated using the equation for incompressible flow. The experiment for collecting data is done on a test bench. The test bench consists of the APS unit and different tanks connected to the APS. Manual valves are used to isolate the circuits from each other and another manual valve is used to empty one of the tanks. A pressure difference between two circuits is created using the manual valves. When the desired pressure difference is achieved, the manual valve isolating the two circuits is opened and the pressure equalization is studied. The constant is then calculated using the least square method, see [4].

3.1.2 Flow when safety valves are open

When the safety valves are open, the flow between the circuits is relatively large. In other words a pressure difference between two circuits is eliminated fast. When studying the pressure equalization, it only takes a few seconds for the pressure in the tanks to equalize. The statement that the flow is relatively large is with respect to how fast the flow is through a small hole of the size that is considered in this thesis (smaller than 10 litres/minute). Since the internal flow is much faster, it is not likely that there will be any noticeable pressure differences between two circuits if there is a small leakage in one of them. Equation (3.1) shows how the pressure difference can be calculated.

3.1.3 Flow over the pressure limiting valve

The flow over the pressure limiting valve is also relatively large. The estimated constant for the equivalent flow area is a little smaller than for the flow over the safety valves, but with no significant difference. Therefore the flow between the high and low pressure circuits can be modelled as static. If there is a leakage in one of the low pressure circuits the flow out from the circuit will be directly compensated by air flowing from the high pressure circuits. The effect that needs to be considered in the model is that the pressure in the low pressure circuits will be limited.

3.1.4 Flow over bypass bleeds

As mentioned before there are two types of bypass bleeds in the system, one-way and two-way bleeds. The flow between the circuits is less over the bypass bleeds than over the other parts of the system. The most important thing though, is the constant pressure difference between two circuits that might occur from a one-way bypass bleed. Pressure equalization between two circuits connected with a one-way bypass bleed will never become zero. The bleed valve requires a small pressure difference before it opens. If the pressure difference is smaller, the bleed will close. This is not the case with two-way bleeds, which are always open in both directions.

3.1.5 Pressure difference from equivalent flow area

If the model for the flow between circuits is rearranged, it is possible to calculate how big the pressure drop between two circuits will be, if there is a leak in one of them. The equation for calculating the pressure difference is:

$$\Delta p = \frac{\dot{m}^2 RT}{p 2 A^2} \tag{3.1}$$

Inserting the estimated constants for the different calculations, gives an idea of how big the pressure difference will be. The conclusion is that for a leakage of 10 litres/min the pressure differences between the circuits are too low, to be able to measure using standard pressure sensors. The noise in the sensors or a small offset in a sensor is larger than the pressure difference.

3.1.6 APS model conclusions

Some aspects from the modelling part are very useful for the diagnosis strategies. The first thing is that before the safety valves have closed the system can be modelled as one high pressure part and one low pressure part. The pressure limiter keeps the pressure almost constant in the low pressure part as long as the pressure in the high pressure part is higher. When the safety valves are open the flow between the circuits is so fast that the circuits directly connected can be modelled as one large circuit.

The one way bypass bleeds will never cause two circuits to get exactly the same pressure. This information is very important for isolating which circuit that is leaking. If a leaking circuit, with closed safety valve, is connected to another not leaking circuit with a one way bypass bleed, the leaking circuit will have a slightly lower pressure than the other circuit. This makes it possible to draw the conclusion that the circuit that has the lower pressure in this case is the circuit that is leaking even if the pressure is decreasing in both circuits.

From the circuit diagram, see Figure 1.1, it is possible to make conclusions of between which circuits this behaviour is possible. A more detailed analysis of the circuits is done in Section 4.4.

3.1.7 Closing of safety valves

The closing of the safety valves are very important in order to isolate which circuit that is leaking. When the safety valves are closed, the circuits are isolated from the other circuits, with the exception of the connections through bypass bleeds. When the safety valves are closing, is not directly specified. The valves are closed by a spring and the pressure level when this is happening varies. In order to handle this, a smart isolation algorithm is needed.

3.2 Pressure drop model

The pressure in the circuits is assumed to be constant if no leakage is present. A perfect system with no leakage does not however exist in today's heavy trucks. This means that there is always a small leak in the compressed air system. The model for the pressure drop in the system is created using the equations from Section 2.1.2 together with the perfect gas law.

When the pressure in the system is high, over 8.5 bar in the high pressure part, the decrease in pressure caused by a leakage is only noticed in the high pressure parts. If there is a leakage in the low pressure part of the system the air will flow from the high pressure part to the low pressure part. The pressure in the low pressure part is constant while the pressure change in the high pressure part is

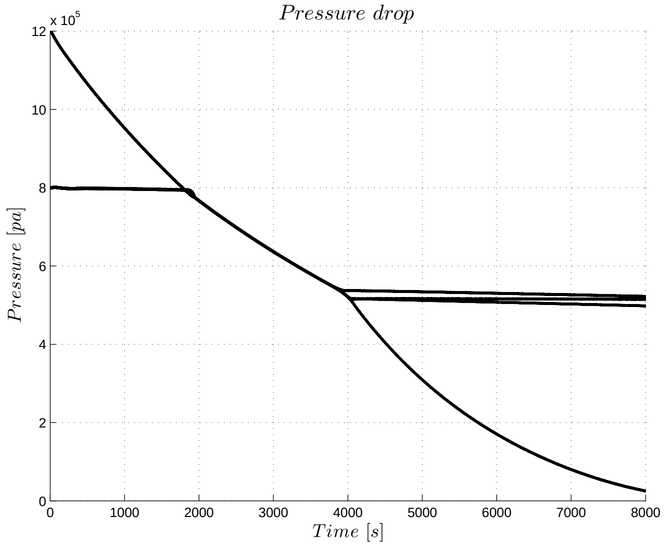

Figure 3.1. A common air pressure change for a leaking heavy truck. In the start the pressure is higher in the high pressure circuits than in the low pressure circuits. When the air leaks out, the pressure in the high pressure circuits decreases. After a while the pressure is the same in all circuits. When the safety valves closes the pressure remains in the non-leaking circuits, and decreases in the leaking circuits.

given by

$$\dot{p} = \frac{\dot{m}RT}{V}. \tag{3.2}$$

Where the expression for the mass flow is given by (2.11). The volume, V, that is considered here is the volume of the tanks in the high pressure part. If the pressure in the system is lower than 8 bar, all circuits will have the same pressure until the safety valves start closing. Equation (2.11) can still be used but the pressure that is considered is the pressure in all circuits and therefore the considered volume should be the total volume in the system. A measured pressure drop for a leaking truck is shown in Figure 3.1. The pressure in the high pressure circuits is in the beginning higher than in the low pressure circuits. After 2000 seconds the pressure in the high pressure circuits has decreased to the same pressure as the low pressure circuits. Since the safety valves are still open the circuits will have the same pressure until the valves start closing after 4000 seconds, because of low pressure. When the safety valves have closed the non leaking circuits hold the pressure well while the pressure in the leaking circuit decreases fast.

3.2.1 Temperature dependency

In (3.2) the pressure is depending on the temperature. In the equation the temperature is considered constant. The temperature change in the system is examined

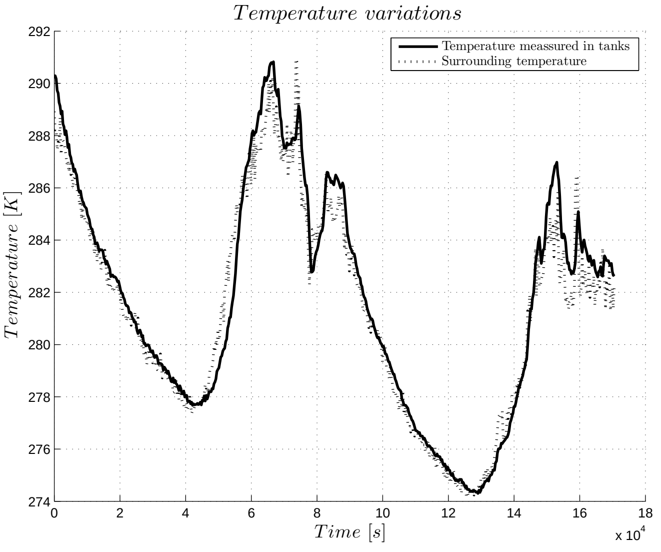

Figure 3.2. Temperature measured in the pressure tanks and the surrounding temperature.

by putting temperature sensors in a heavy truck. The temperature in the vehicle is measured when the vehicle is turned off after driving. The results are showing that the temperature in the system is close to the ambient temperature, see Figure 3.2. Therefore the temperature change in the system is small as long as the surrounding temperature is constant. In a simplified model the temperature can be approximated to be constant.

However, for small leakages the model needs to be very exact to make the right diagnosis and the temperature needs to be considered. First of all (2.11) is depending on the temperature as $T^{-\frac{1}{2}}$. A temperature difference of 20K from 273K to 293K for a fixed area increases the mass flow by 3.6%. This will make the estimated area to be 3.6% larger if the temperature used in the model is 273K. On the other hand, an increase in temperature will result in higher pressure in the tanks. The change in pressure caused by temperature changes can be calculated by using the ideal gas law as

$$\frac{T_2}{T_1} = \frac{p_2}{p_1},$$

where p_i is the pressure in the system at temperature T_i. If the temperature of the air is increased with 20K as above, the pressure increases 7%. The corresponding pressure measurements to Figure 3.2 is shown in Figure 3.3. The truck where the measurements come from is almost not leaking at all and therefore the temperature variations are seen clearly in the pressure variations. To get an idea of how much influence the temperature has on the detection performance a simple example is considered in Section 3.2.2.

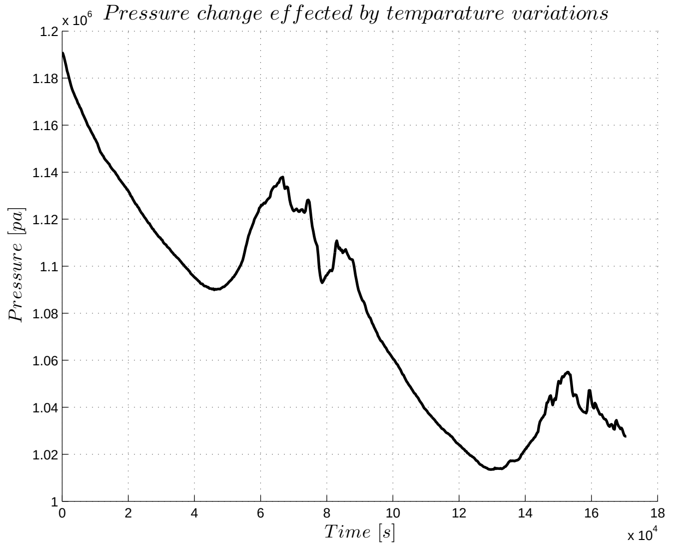

Figure 3.3. Pressure change in high pressure circuits with temperature variations. The corresponding temperature in the system is shown in Figure 3.2.

3.2.2 Temperature change model

The air temperature in the system is depending on the temperature of the delivered air from the compressor and the surrounding temperature. Since the air is stored in steel tanks with good heat transfer capability, the air temperature in the tanks is modelled to be the same as the surrounding temperature.

Temperature change example

Assume that the model given by (3.2) is correct. If a small hole of $0.1mm\varnothing$ is made on a reservoir of the size $100dm^3$ with 10 bar absolute pressure, the pressure will decrease to 9.47 bar in one hour if the temperature is 273K. However, if the temperature during this time actually increases 10K, assumed to be a linear increase for simplicity, the pressure after the same time will be 9.82 bar. The simulated pressure change, both with and without temperature change, is shown in Figure 3.4. If the model without temperature compensation, assuming the temperature is constant at 273K, is used to simulate the pressure drop, the size of a hole that would give the same final pressure would be $0.058mm\varnothing$. The different area sizes gives a percentage error of 66%.

If an even smaller hole than $0.1mm\varnothing$ is used, for example 0.05mm, the pressure after one hour with constant temperature of 273K would be 9.87 bar. If the temperature is increased according to before the pressure would end up at 10.2 bar. This means that if the temperature changes fast for a tank with a small leakage, the pressure will increase because of temperature changes faster than the pressure is dropping because of the leak. The pressure change for a hole

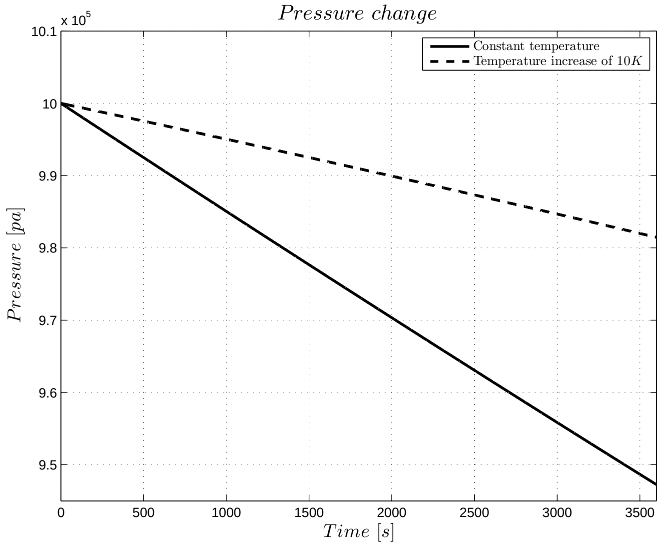

Figure 3.4. Simulated pressure change for a $100dm^3$ tank with a hole of $0.1mm\varnothing$. The temperature increases linear over time.

of $0.05mm\varnothing$ is shown in Figure 3.5. If the temperature on the other hand is decreasing, the simulated pressure drop with no temperature compensation will be too slow. That means that a larger area is needed to accomplish the same pressure drop as for the model with temperature compensation. If the model with no temperature compensation is used in order to estimate the hole area, assuming that it was unknown, it would be estimated to be larger than it actually is.

However if the hole is large, for example $0.5mm\varnothing$, the differences caused by temperature changes is not as big as for small holes, for example $0.05mm\varnothing$. If the temperature is constant the pressure drops to 2.58 bar. If the temperature is increased the final pressure would be 2.64 bar. The leakage area that would give a final pressure of 2.58 bar, if there is a 10K temperature increase, is a hole with a diameter of $0.504mm\varnothing$. The conclusion is that the temperature compensating model is needed in order to model small leakages but for larger ones the results are barely affected, see Figure 3.6.

3.2.3 Flow between high and low pressure circuits

Even if there is a pressure limiter between the high and the low pressure circuits, to keep the pressure in the low pressure circuits constant, some small changes in the pressure are present. The pressure can either increase or decrease over time. When the air mass is increasing in the low pressure circuits it is because the pressure limiter is letting small amounts of air flow from the high pressure circuits in to the low pressure circuits. If only the pressure change is studied for the high pressure circuits, assuming the low pressure circuits is at a constant lower pressure around

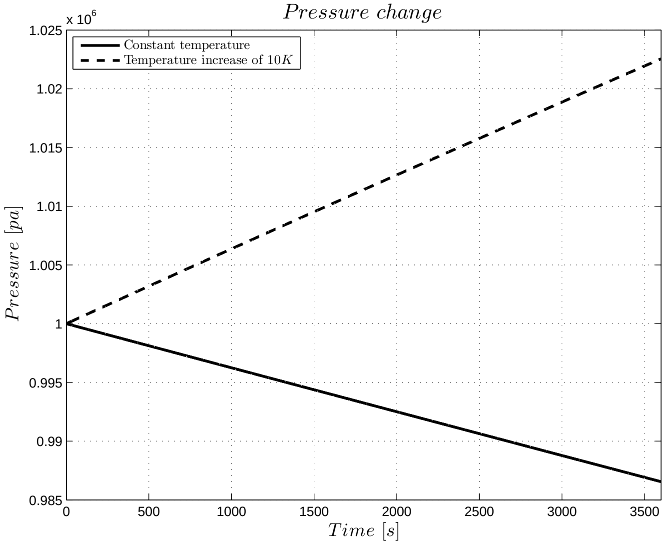

Figure 3.5. Simulated pressure change for a $100dm^3$ tank with a hole of $0.05mm\varnothing$. The temperature increases linear over time.

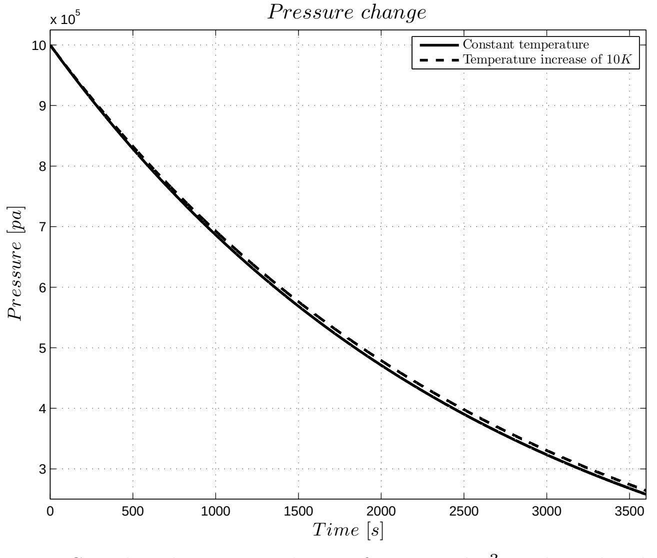

Figure 3.6. Simulated pressure change for a $100dm^3$ tank with a hole of $0.5mm\varnothing$. The temperature increases linear over time.

8 bar, the estimated leakage area might be estimated wrong. A pressure drop in the high pressure circuits may not always depend on a leakage or temperature change, but on air flowing to the low pressure circuits even if there is no leakage in those circuits either. The pressure change model given by (3.2) can be extended or a small change of the model can be done as described in Section 3.2.4.

3.2.4 Simplifying model implementation

To expand the model to include temperature changes over time and also the flow between the different circuits, some changes are preferably made. This will especially make the modelling easier when using the LMS to estimate the leakage area. Instead of calculating the change in pressure, the mass of air in the system is considered. The perfect gas law can be used to calculate the mass of air in the system at a specific time. The mass flow can then be calculated by the difference of mass at two different samples, divided by the sample time. From Section 2.1.2 equation (2.11) also gives an expression for the mass flow. The mass flow in the equation is indirectly measured by measuring the pressure and temperature in the system and since it is the total mass in the system that is calculated in every time step the flow between the circuits are directly compensated for. The total mass of air in the system is given by

$$m = \frac{p_{high}V_{high} + p_{low}V_{low}}{RT}. \tag{3.3}$$

3.3 Energy consumption

There are two different kinds of energy consumptions that need to be considered in this thesis. The first one is the amount of fuel that the compressor uses to produce air. The other energy amount is the electrical energy that is used by the diagnosis algorithm. Since the measurements is planned to be performed when the vehicle is turned off the electrical energy consumption needs to be limited.

3.3.1 Energy usage by the compressor

If there is a leakage in the system, the compressor has to work more often and therefore consume more energy. The amount of fuel that is needed to compensate for air leaking out from the system can be calculated if the compressor and the combustion engine efficiencies is known. To do a simple calculation a long-haulage truck is studied. The benefits for study a long-haulage vehicle is that the speed is constant since the driving is mostly on highway. The compressor efficiency depends on the speed of the compressor and the back pressure. The exact amount of energy that is needed to feed 1 litre of air to the compressed air system, for a given compressor speed and back pressure, can be found in the manufacture data sheet. The needed energy for the compressor has to be generated by the engine. The efficiency of the engine gives how much extra diesel fuel the engine consumes to drive the compressor. The extra fuel that is needed can then be compared to the fuel consumption for the vehicle in order to get the percentages in increased fuel consumption. Previous calculations at Scania gives that the consumption increases up to 0.01-0.02% for every litre air leaking, a 10 litre/minute leak gives 0.1-0.2% increased fuel consumption.

3.3.2 Energy usage by diagnosis algorithm

The diagnosis algorithm should be designed to be implemented in the APS control unit and the electrical energy consumption for the algorithm should be as low as possible. If the electrical energy consumption is too high, the battery might be drained. Also one of the main reasons to implement a leakage detection algorithm is to save fuel by detecting the leakages so they can be repaired. If the algorithm uses too much energy the profit of detecting the leakages will be wasted.

Chapter 4

Diagnosis algorithm

The APS unit regenerate, letting air flow backwards through the dryer, every time the vehicle is turned off. The regeneration can take up to ten minutes before it is complete. The regeneration has to complete before starting the diagnosis algorithm since it consumes air which can result in a false alarm. The pressure is then measured for a predetermined time and sample rate. The effective leakage area is estimated and compared to a threshold to see if the leakage is larger than the maximum allowed leakage size. If there is a leakage the value of the estimated leakage area is used to predict when the circuits have been isolated, that is when the safety valves have closed. Between from when the leakage is detected to the point where the circuits have divided, the APS control unit can go into sleep mode to save energy. The isolation algorithm starts when the circuits have divided. The algorithm estimates the leakage area in all circuits individually and the results are used to rank the circuits in leaking order. This can for example be used by a mechanic to easier find the leakage. A flow chart for the algorithm is shown in Figure 4.1. In the first step the total leakage area for the pressure system is estimated. If the leakage area is larger than a predetermined limit, threshold, the algorithm estimates when the circuits have divided. The isolation algorithm estimates the leakage area for the circuits with pressure sensors and a result is given of which circuit that leaks the most.

4.1 Parameter estimation

One way of detecting leakages is to estimate the leakage area. To estimate the leakage area, the LMS-method, [4], is implemented together with the model from Section 3.2.4. The mass is given by (3.3) and the calculated mass flow $\hat{\dot{m}}$ is given by

$$\hat{\dot{m}}(t) = \frac{m(t) - m(t-\tau)}{\tau}. \tag{4.1}$$

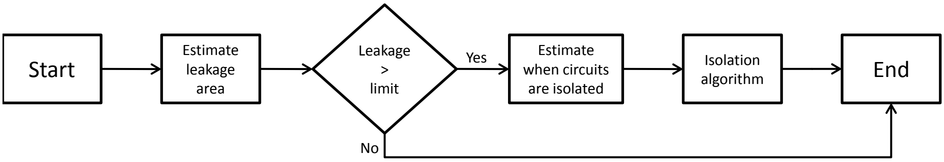

Figure 4.1. Overview flow chart for the diagnosis algorithm. The algorithm starts after the APS has regenerated. First an estimation of the total leakage area in the system is performed. If the leakage size is larger than a predetermined limit the algorithm estimates when the safety valves have closed. When the safety valves have closed, it is possible for the isolation algorithm to point out which circuit that leaks the most.

By using (2.14), letting the calculated mass flow be denoted as $y(t)$ and, to get an easier overview, introducing a new variable, $\varphi(t-1)$, gives

$$y(t) = -A\sqrt{\frac{\gamma}{R}}\frac{p(t-1)}{\sqrt{T}}\left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}} = -A\varphi(t-1). \tag{4.2}$$

The minus sign in (4.2) is introduced because the mass flow is out from the tank. From this equation the LMS estimation of the leakage area, $\hat{A}$, is

$$\hat{A}(t) = \hat{A}(t-1) + \mu\varphi(t-1)\left(y(t) - \varphi(t-1)\hat{A}(t-1)\right) \tag{4.3}$$

where μ is a design parameter that needs to be tuned for the desired performance. The main trade off when tuning the filter is the estimation time and the repressing of measurement noise. The size of the leakage also needs to be considered when tuning the filter. For a large leak the filter takes longer time to reach its maximum value than it takes for a small leakage.

4.1.1 Temperature compensation

To get a better estimation of the leakage area, the temperature changes need to be considered. The trade off however is that the temperature sensors have measurement noise. Therefore the estimation is only better when the temperature change is large and the leakage area is small. When the temperature is constant only the initial temperature is needed to get at good estimation of the leakage area. If the leakage area is large a temperature change is in general affecting the estimation very little.

The results from the LMS estimation on a small leakage with a temperature change over time is shown in Figure 4.2, with the corresponding temperature shown in Figure 4.3. The temperature change is taking place in the beginning of the estimation, which in this case is done continuously over a long time period with a temperature drop of totally $6K$. It is easily noticed that the estimation of the leakage area is larger in the beginning when the temperature drop occurs. The

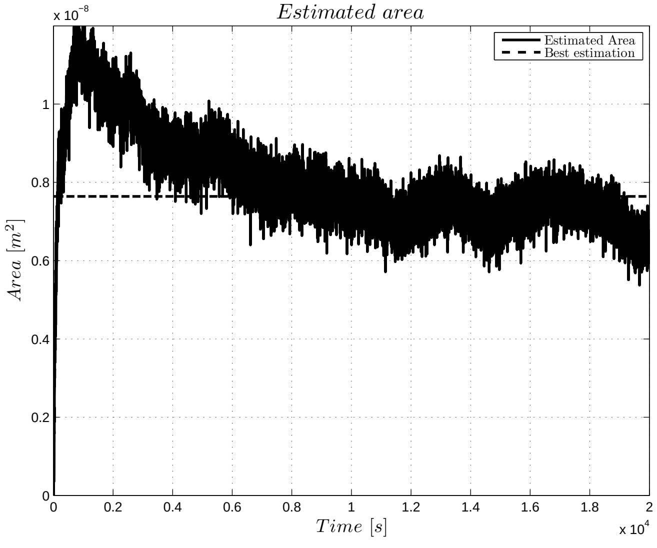

Figure 4.2. Estimated leakage area without temperature compensation. The estimation deviates from the best estimation in the beginning because of the constant temperature assumption.

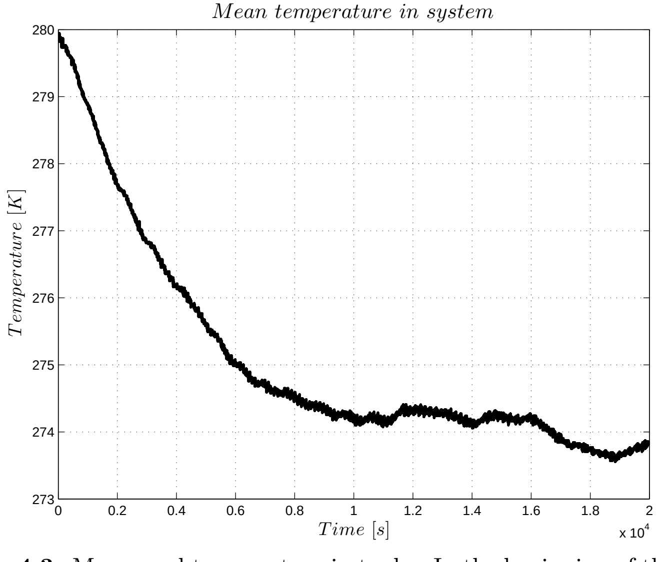

Figure 4.3. Meassured temperature in tanks. In the beginning of the test the surrounding temperature decreases, causing the air temperature in the tanks to decrease.

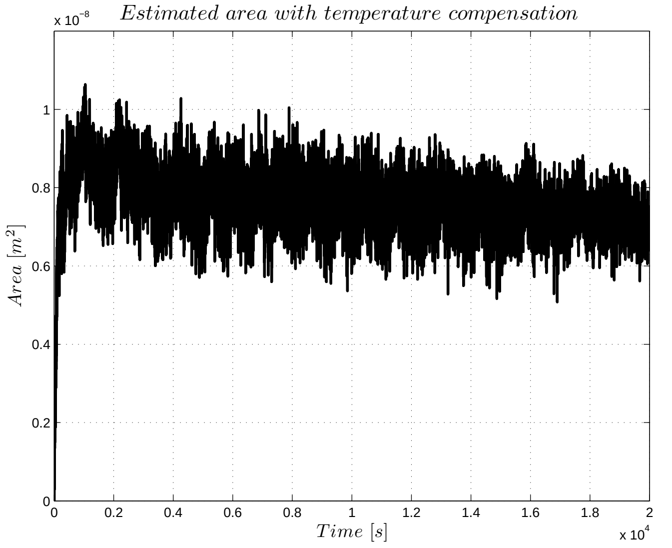

Figure 4.4. Estimated leakage area with temperature compensation. The estimation is better during the change of the temperature (Figure 4.3), compared to Figure 4.2.

results are expected since the pressure in the tank decreases because of both the temperature drop and the leakage. If the model however does not compensate, for temperature changes, the increased pressure drop will result in a larger estimated area.

When the temperature change is considered in the model, using measured temperature in (4.2) instead of using a fixed constant value, the estimation is more constant and not over estimating the area in the beginning of the measurements. The results from the same measurements as in Figure 4.2 but with compensation for temperature changes is shown in Figure 4.4. By comparing Figure 4.2 and Figure 4.4, it can be seen that the estimation in the beginning is smaller when the temperature change is compensated for. It can also be seen that the estimations using temperature sensors have more measurement noise than the one without. In this case the temperature compensation makes the estimations better, the difference between the maximum and minimum estimated leakage area is smaller. If the temperature compensation however is used on a leakage that is large the advantage for using temperature compensation is almost negligible, see Section 3.2.2.

4.1.2 Estimation at different pressures

One problem with the estimation of the leakage area, when making the decision whether to alarm or not, is that it is not known in which circuit a possible leakage is present. The mass flow out from the tanks is depending on the leakage area, the temperature and the pressure in the tank. If the pressure is high, the mass

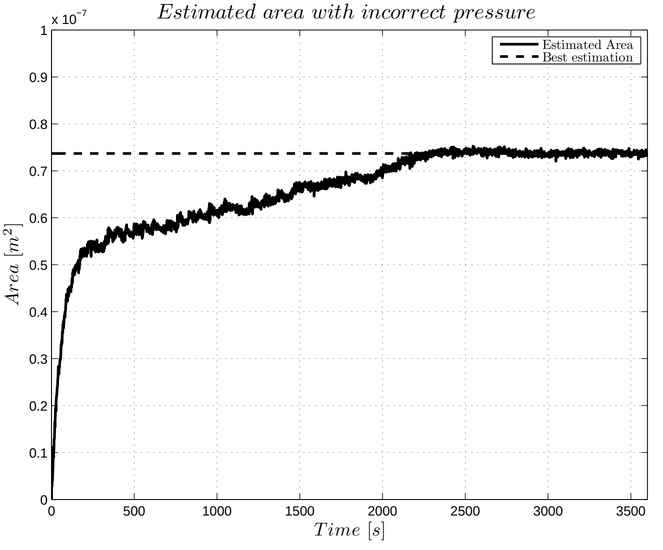

Figure 4.5. Estimated leakage area using the incorrect pressure. The error in the estimation decreases when the pressure in the high pressure tanks decreases. At 2300 seconds the pressure is the same in the high and low pressure circuits.

flow is larger than if the pressure is low, if the leakage area and temperature are the same.

Most of the time when the vehicle is turned off, the pressure in the high pressure circuits is higher than the pressure in the low pressure circuits. If the leakage is assumed to be in the high pressure part, but actually is in the low, the estimated area will be too small. The error that occurs in the estimated area is the ratio between the pressure in the high and low pressure parts. The equation for how the mass flow depends on leakage area and pressure is shown in (4.2), the mass flow is proportional to the product of the area and the pressure. Therefore the estimated area will depend on which p (high pressure or low pressure), that is used.

Measurements show that the pressure in a vehicle after it has been turned off and the APS has regenerated, is between 8-12 bar. If the pressure in the high pressure circuit is 10 bar the pressure ratio between the high and low pressure circuits is 0.8. If the wrong pressure is used in the estimation, an error, which size depends on the pressure ratio, occurs. If the higher pressure is always used in the estimations, the results might be too small if the leakage actually is in a low pressure circuit. This might lead to a missed detection situation, where a leakage actually is larger than an accepted threshold. But due to the underestimation, the alarm might not be triggered. On the other hand if the lower pressure is used, the leakage area might be estimated too large leading to false alarms. Figure 4.5 shows the estimated area, using the high pressure in the estimation, for a leakage that actually is in a low pressure circuit. The under estimation can be seen by comparing the results with Figure 4.6, where the low, correct for this leakage, pres-

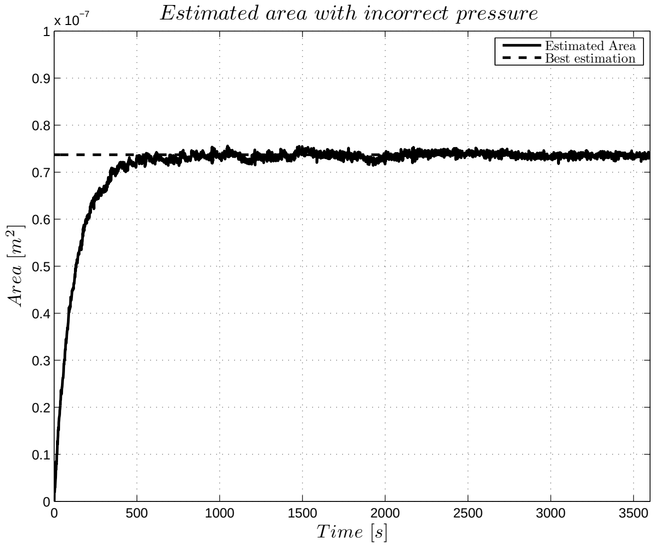

Figure 4.6. Estimated leakage area using the correct pressure. The estimation is not too low in the beginning , compare to Figure 4.5, even if there is a difference in pressure between the high and low pressure circuits.

sure is used. It can be seen that there is a significant difference in the beginning of the estimation of about 25%. When the pressure in the high pressure circuits decreases, the pressure difference between the high and low pressure circuits' decreases. Therefore, the estimation in Figure 4.5 and 4.6 becomes less different, since the pressure ratio between high and low pressure circuits decreases. In Figure 4.5 and Figure 4.6 the pressure in the high and low pressure circuits are 11 and 8 bar at the beginning. After 2200 seconds the pressure in the high pressure circuit has decreased to 8 bar.

4.1.3 Isolation of high or low pressure circuit

The problems mentioned in Section 4.1.2, that the estimation becomes incorrect if the wrong pressure is used, can be compensated for and also gives information about in which type of circuit, high pressure or low pressure, the leakage is present. A drift in the estimation occurs when the incorrect pressure is used, see Figure 4.5. This drift is useful, because if it can be detected, it gives information of where the leakage is present. If the pressure for the high pressure circuits is used but the leakage actually is in the low pressure circuit the estimated leakage area will increase until the pressure in the high and low pressure circuits are the same. By doing two estimations it is possible to determine if the leakage is in a high or low pressure circuit. If the pressure for the high pressure circuits is used and the estimated area is larger when it is estimated at a lower pressure, below 8 bar, the leakage is in one of the low pressure circuits. If the leakage area is the same in both estimations the leakage is in a high pressure circuits. This information is very useful when doing the isolation.

Making two estimations

The first estimation should be done as early as possible, that is directly after the vehicle is turned off and the APS has regenerated. The reason why the first estimation has to be done as fast as possible is that the accuracy is increased when there is a larger pressure difference between the high and low pressure circuits. A simplified representation of the model (4.2) is

$$\dot{m} = ApC, \tag{4.4}$$

where C is a constant. If the pressure in the high pressure circuits, p_1, is used in (4.4) and the leakage is in the high pressure circuits, the estimation will be correct. If the leakage is in the low pressure circuit, the p that is used in (4.4) would be incorrect. If p_1 is larger than the pressure in the low pressure circuits the estimated area becomes too small. The LMS tries to satisfy (4.4) and therefore a too large p would give a too small A.

The next estimation is done when the pressure in the high and low pressure circuits is equal. Since the pressure is the same in all circuits the estimated area will be correct, because the use of wrong pressure as input to the algorithm is impossible since all pressure sensors give the same value. If the first estimation is called A_1 and the second estimated area A_2 and

$$A_1 = A_2,$$

then the first estimation was done with the correct pressure. If not, the leakage is in the other type of pressure circuit than was assumed at the first estimation.

The second estimation is done after that the pressure in the high and low pressure circuits have become equal. The difference in the estimated area, if using the incorrect pressure in the first estimation, is directly proportional to the pressure ratio between the pressure differences between the high and low pressure circuits in the first estimation. The relation is given by

$$\frac{A_{large}}{A_{small}} = \frac{p_1}{p_2},$$

where A_{large} is the larger of the two estimated areas, A_{small} is the smaller. To get a threshold for when to make the decision that the wrong pressure was used, the half theoretical value is used. The threshold is calculated as

$$J_{high/low} = 1 + \frac{\frac{p_1}{p_2} - 1}{2}.$$

If the leakage was assumed to be in the high pressure circuit in the first estimation and the area ratio is larger than the threshold

$$\frac{A_2}{A_1} > J_{high/low}$$

the wrong pressure is assumed to have been used in the first estimation. Therefore it is known that the leakage is in the low pressure circuit.

A flow chart for the diagnosis algorithm with two estimations is showed in Figure 4.7. The difference between the flow chart in Figure 4.1 is that after the decision if $Lekage > limit$ is made, resulting Yes, a second estimation of the leakage area is done. The result if the leakage is in a high or low pressure circuit is used by the isolation algorithm to isolate the leakage to the correct circuit.

4.2 Amount of data needed

The amount of data that is needed depends on what and how good performance that is wanted from the diagnosis system. If more data is collected the filter constant in the LMS can be chosen smaller to suppress noise more effectively. The disadvantage of having a too slow filter is in the case where the leakage size is decreasing when the pressure decreases, see Section 4.5.

The most limiting factor is the possibility to use the estimation strategy described in Section 4.1.3. In order to make it possible for the algorithm to give good results, the first estimation must be carried out fast. If the first detection takes too much time, the pressure difference between the high and low pressure circuits will have disappeared before the estimation is complete. The estimated area in the second estimation will therefore always be the same and the information about in what type of circuit the leakage is in, cannot be given. Figure 4.8 shows a simulation of a pressure drop for a 100 litre tank with a leakage of 10 litres/minute. The start pressure is 12 bar which is almost the highest possible after that a truck has been turned off and the APS has regenerated. The APS safety valves start closing around 5.5 bar, which is reached after 4000 seconds in Figure 4.8. Therefore, the estimation time cannot be longer than 4000 seconds. If the estimation takes longer time the circuits will start isolating from each other before the estimation is complete. To be able to do the isolation between faults in the high and low pressure circuits the first estimation must be completed before the high and low pressure circuits reaches the same pressure, around 8 bar. In Figure 4.8 the pressure reaches 8 bar after 2000 seconds. However, to do the isolation there should be some differences between the high and low pressure circuits to get at least a pressure difference of 1 bar, the longest estimation time for the first estimation should not be longer than 1500 seconds.

If the performance in the estimation is more important than the isolation, another way to distribute the samples is, to instead of sampling a lot during a short time period, spread the samples over a wider period of time. The samples can for example be taken one sample every tenth minute. The advantage of spreading the samples is that the pressure changes more between the samples, making the measurement less influenced by measurement noise. The down side with spreading the samples is that a longer detection time probably is needed, making it more difficult to do the isolation between the high and low pressure circuit.

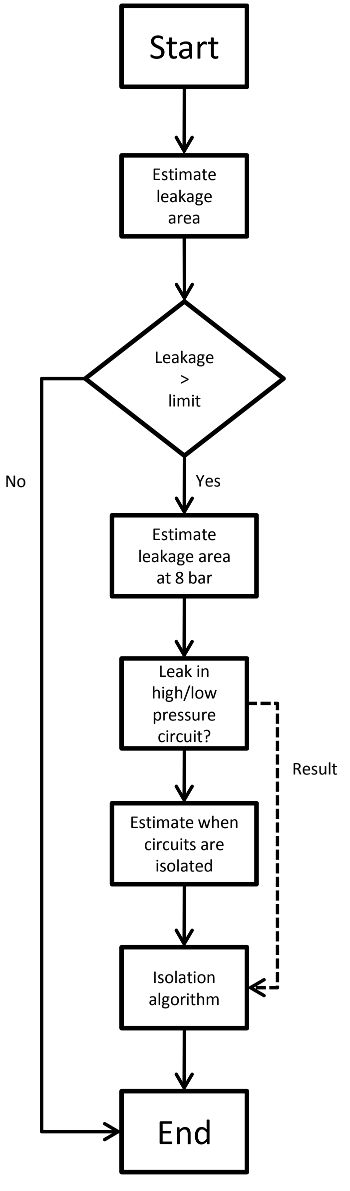

Figure 4.7. Flow chart for diagnosis algorithm with two estimations before circuits isolates. After that the first estimation is done, and there is a leakage, a second estimation is performed. From the results from the two estimations it is possible to tell if the leakage is in a high or low pressure circuit. This information is used by the isolation algorithm to isolate which circuit that is leaking. The isolation algorithm starts after that the safety valves have closed and the circuits isolated from each other.

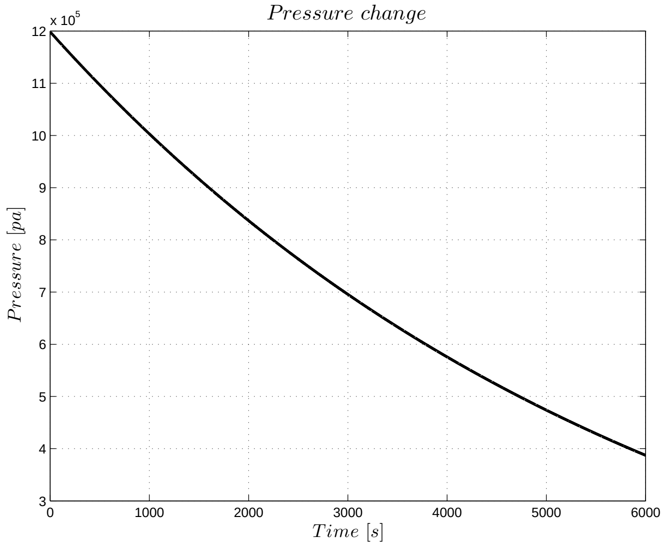

Figure 4.8. Simulated pressure drop for a 100 litre tank with a 10 litre/minute leakage. The pressure has decreed to 8 bar after about 2000 seconds. The first estimation in the diagnosis algorithm must be performed before the pressure is below 8 bar.

4.2.1 Sampling every second

When the parameter estimation is done by taking samples every second, the time that is needed in order to suppress most of the noise is around ten to twenty minutes. The advantage of using a short period of time is that it is possible to get a result fast and that the leakage can be isolated to be in either the high or low pressure circuit. If the filter is too slow the possibility to do the isolation might be missed.

Filter tuning one sample every second

To find the parameter μ, the LMS estimations from a real truck is used. The test is done with both small and large leakages. For the test three different filter constants are used. The estimation time is studied (the time it takes for the filter to reach the settling value), if the leakage is isolated to be in the right type of circuit (high or low pressure), and how close the result is to the best estimation are studied. Table 4.3 shows the results from measurements done with eight different measurements. The results show that the fastest filter has advantages for the isolation of the high and low pressure circuit. For the tests both the high and low pressure are used in the first estimation, Table 4.2 shows the results when the low pressure is used and Table 4.3 when the high pressure is used. The corresponding pressure drops can be found in Appendix A. If the estimation is too slow to complete the first estimation before the high and low pressure circuits got the same pressure is marked with "-". The settling time for the different filter parameters, μ in (4.3), is shown in Table

Table 4.1. Parameters used as μ in (4.3) when sampling with 1Hz. C is a constant that is introduced to show the relative differences between the parameters. A small parameter value gives a better suppression of measurement noise but a longer settling time than a larger parameter value.

Parameter	Parameter value	Settling time [s]
μ_1	$4C$	300
μ_2	$2C$	600
μ_3	C	1200

4.1. The advantage of using a slower filter is that the estimation of the leakage area becomes more accurate. This can be seen by comparing the columns A_2 which is the estimated area at correct pressure, the high and low pressure circuits have the same pressure, with $A^\star$ which is the best estimation of the leakage area.

Table 4.2 and Table 4.3 show that the results for estimating in which type of circuit the leakage is in, are the same. All parameter settings give an incorrect result for data set number 2. The leakage that is used in this measurement is small, smaller than a leakage of 1 litre/minute, and for these leakages the algorithm seems to have problem to give the correct results. The same leakage size is used in data 1 for which the correct results is given when using μ_2 and μ_3. The reason for why the algorithm fails when using μ_1 is probably because too little measurement data is used and therefore the estimations is not accurate enough.

When μ_3 is used with data 5 and data 8, the isolation is missed since the settling time is too long. The reason for why not also data 4 and data 7 gives a failure is that the pressure in those two measurements is extra high, around 12 bar, when the initial pressure in the other measurements that is used is around 10 bar.

The conclusion given by studying Table 4.2 and Table 4.3 is that a too large parameter gives uncertainties in the estimations that can lead to an incorrect result from the algorithm. With a too small parameter the algorithm misses to do the isolation between high and low pressure circuit.

4.2.2 Sampling once every tenth minute

In order to decrease the noise in the estimations, a longer period of time can be used for the detection. To avoid increasing the energy consumption, the samples can be spread out to be taken once every tenth minute. The advantage of spreading the samples, is that the pressure change between the samples is larger than if there is only one second between the samples. This results in an estimation that is less affected by the noise in the sensors. When the samples are spread out more, the numbers of samples can also be decreased.

Table 4.2. Results when sampling with 1Hz. The pressure that has been used in the first estimation is the pressure in the low pressure circuits. Eight different measurements is studied. The real location of the leakage is presented and can be compared to the estimated location. For small leakages the smallest parameter give a incorrect result, see μ_1 Data 1. For larger leakages the settling time for the smallest filter constant is too long. The pressure decrees below 8 bar before the estimation is complete, making the isolation if the leakage is in a high or low pressure circuit impossible, see μ_1 for Data 5 and Data 8.

Data	μ_x	A_1	A_2	$A^\star$	$\frac{A_1}{A_2}$	$J_{high/low}$	Location	Estimated location
1	μ_1	$1.04 \cdot 10^{-8}$	$7.16 \cdot 10^{-9}$	$7.64 \cdot 10^{-9}$	1.46	1.13	Low	High
1	μ_2	$7.63 \cdot 10^{-9}$	$7.35 \cdot 10^{-9}$	$7.64 \cdot 10^{-9}$	1.04	1.13	Low	Low
1	μ_3	$7.63 \cdot 10^{-9}$	$7.29 \cdot 10^{-9}$	$7.64 \cdot 10^{-9}$	1.05	1.12	Low	Low
2	μ_1	$1.16 \cdot 10^{-8}$	$8.10 \cdot 10^{-9}$	$7.64 \cdot 10^{-9}$	1.43	1.08	Low	High
2	μ_2	$1.01 \cdot 10^{-8}$	$7.87 \cdot 10^{-9}$	$7.64 \cdot 10^{-9}$	1.29	1.08	Low	High
2	μ_3	$8.69 \cdot 10^{-9}$	$7.25 \cdot 10^{-9}$	$7.64 \cdot 10^{-9}$	1.20	1.07	Low	High
3	μ_1	$1.99 \cdot 10^{-8}$	$1.37 \cdot 10^{-8}$	$1.57 \cdot 10^{-8}$	1.45	1.06	High	High
3	μ_2	$1.85 \cdot 10^{-8}$	$1.57 \cdot 10^{-8}$	$1.57 \cdot 10^{-8}$	1.18	1.06	High	High
3	μ_3	$1.81 \cdot 10^{-8}$	$1.52 \cdot 10^{-8}$	$1.57 \cdot 10^{-8}$	1.19	1.04	High	High
4	μ_1	$1.73 \cdot 10^{-8}$	$1.71 \cdot 10^{-8}$	$1.57 \cdot 10^{-8}$	1.01	1.09	Low	Low
4	μ_2	$1.66 \cdot 10^{-8}$	$1.72 \cdot 10^{-8}$	$1.57 \cdot 10^{-8}$	0.96	1.08	Low	Low
4	μ_3	$1.69 \cdot 10^{-8}$	$1.77 \cdot 10^{-8}$	$1.57 \cdot 10^{-8}$	0.96	1.07	Low	Low
5	μ_1	$7.57 \cdot 10^{-8}$	$6.63 \cdot 10^{-9}$	$7.09 \cdot 10^{-8}$	1.14	1.06	High	High
5	μ_2	$7.43 \cdot 10^{-8}$	$6.60 \cdot 10^{-9}$	$7.09 \cdot 10^{-8}$	1.12	1.03	High	High
5	μ_3	$6.90 \cdot 10^{-8}$	-	$7.09 \cdot 10^{-8}$	-	-	High	-
6	μ_1	$6.90 \cdot 10^{-8}$	$7.23 \cdot 10^{-8}$	$7.09 \cdot 10^{-8}$	0.95	1.20	Low	Low
6	μ_2	$7.20 \cdot 10^{-8}$	$7.17 \cdot 10^{-8}$	$7.09 \cdot 10^{-8}$	1.00	1.18	Low	Low
6	μ_3	$7.29 \cdot 10^{-8}$	$7.12 \cdot 10^{-8}$	$7.09 \cdot 10^{-8}$	1.02	1.13	Low	Low
7	μ_1	$1.40 \cdot 10^{-7}$	$1.02 \cdot 10^{-7}$	$1.08 \cdot 10^{-7}$	1.38	1.16	High	High
7	μ_2	$1.32 \cdot 10^{-7}$	$1.03 \cdot 10^{-7}$	$1.08 \cdot 10^{-7}$	1.27	1.11	High	High
7	μ_3	$1.17 \cdot 10^{-7}$	$1.02 \cdot 10^{-7}$	$1.08 \cdot 10^{-7}$	1.15	1.03	High	High
8	μ_1	$1.08 \cdot 10^{-7}$	$1.05 \cdot 10^{-7}$	$1.08 \cdot 10^{-7}$	1.03	1.07	Low	Low
8	μ_2	$1.08 \cdot 10^{-7}$	$1.04 \cdot 10^{-7}$	$1.08 \cdot 10^{-7}$	1.03	1.03	Low	Low
8	μ_3	$1.06 \cdot 10^{-8}$	-	$1.08 \cdot 10^{-7}$	-	-	Low	-

Table 4.3. Results when sampling with 1Hz. The pressure that has been used in the first estimation is the pressure in the high pressure circuits. The results for estimating if the leakage is in a high or low pressure circuit is the same as when the low pressure is used, see Table 4.2.

Data	μ_x	A_1	A_2	$A^\star$	$\frac{A_2}{A_1}$	$J_{high/low}$	Location	Estimated location
1	μ_1	$8.76 \cdot 10^{-9}$	$7.13 \cdot 10^{-9}$	$7.64 \cdot 10^{-9}$	0.81	1.13	Low	High
1	μ_2	$5.72 \cdot 10^{-9}$	$7.05 \cdot 10^{-9}$	$7.64 \cdot 10^{-9}$	1.23	1.13	Low	Low
1	μ_3	$6.03 \cdot 10^{-9}$	$7.10 \cdot 10^{-9}$	$7.64 \cdot 10^{-9}$	1.18	1.12	Low	Low
2	μ_1	$9.48 \cdot 10^{-9}$	$8.12 \cdot 10^{-9}$	$7.64 \cdot 10^{-9}$	0.86	1.08	Low	High
2	μ_2	$8.66 \cdot 10^{-9}$	$7.88 \cdot 10^{-9}$	$7.64 \cdot 10^{-9}$	0.91	1.08	Low	High
2	μ_3	$7.56 \cdot 10^{-9}$	$7.27 \cdot 10^{-9}$	$7.64 \cdot 10^{-9}$	0.96	1.07	Low	High
3	μ_1	$1.77 \cdot 10^{-8}$	$1.38 \cdot 10^{-8}$	$1.57 \cdot 10^{-8}$	0.78	1.06	High	High
3	μ_2	$1.66 \cdot 10^{-8}$	$1.57 \cdot 10^{-8}$	$1.57 \cdot 10^{-8}$	0.95	1.06	High	High
3	μ_3	$1.66 \cdot 10^{-8}$	$1.52 \cdot 10^{-8}$	$1.57 \cdot 10^{-8}$	0.92	1.04	High	High
4	μ_1	$1.43 \cdot 10^{-8}$	$1.68 \cdot 10^{-8}$	$1.57 \cdot 10^{-8}$	1.18	1.09	Low	Low
4	μ_2	$1.42 \cdot 10^{-8}$	$1.82 \cdot 10^{-8}$	$1.57 \cdot 10^{-8}$	1.28	1.08	Low	Low
4	μ_3	$1.49 \cdot 10^{-8}$	$1.75 \cdot 10^{-8}$	$1.57 \cdot 10^{-8}$	1.18	1.07	Low	Low
5	μ_1	$6.73 \cdot 10^{-8}$	$6.61 \cdot 10^{-9}$	$7.09 \cdot 10^{-8}$	0.98	1.06	High	High
5	μ_2	$6.87 \cdot 10^{-8}$	$6.61 \cdot 10^{-9}$	$7.09 \cdot 10^{-8}$	0.96	1.03	High	High
5	μ_3	$6.85 \cdot 10^{-8}$	-	$7.09 \cdot 10^{-8}$	-	-	High	-
6	μ_1	$5.00 \cdot 10^{-8}$	$7.07 \cdot 10^{-8}$	$7.09 \cdot 10^{-8}$	1.42	1.20	Low	Low
6	μ_2	$5.35 \cdot 10^{-8}$	$7.10 \cdot 10^{-8}$	$7.09 \cdot 10^{-8}$	1.33	1.18	Low	Low
6	μ_3	$5.76 \cdot 10^{-8}$	$7.11 \cdot 10^{-8}$	$7.09 \cdot 10^{-8}$	1.23	1.13	Low	Low
7	μ_1	$1.06 \cdot 10^{-7}$	$1.01 \cdot 10^{-7}$	$1.08 \cdot 10^{-7}$	0.95	1.16	High	High
7	μ_2	$1.05 \cdot 10^{-7}$	$1.03 \cdot 10^{-7}$	$1.08 \cdot 10^{-7}$	0.98	1.11	High	High
7	μ_3	$1.05 \cdot 10^{-7}$	$1.02 \cdot 10^{-7}$	$1.08 \cdot 10^{-7}$	0.96	1.03	High	High
8	μ_1	$9.47 \cdot 10^{-8}$	$1.04 \cdot 10^{-7}$	$1.08 \cdot 10^{-7}$	1.10	1.07	Low	Low
8	μ_2	$9.94 \cdot 10^{-8}$	$1.04 \cdot 10^{-7}$	$1.08 \cdot 10^{-7}$	1.05	1.03	Low	Low
8	μ_3	$1.05 \cdot 10^{-7}$	-	$1.08 \cdot 10^{-7}$	-	-	Low	-

Filter tuning one sample every tenth minute

When the samples are spread out more, the detection/settling time needs to be longer than the shortest time which was used when sampling at 1Hz. This is because a few samples have to be gathered in order to make the estimation. If a too large filter constant is used the filter becomes unstable. To get a stable filter, about 4 samples are needed, which gives a detection time of approximately 30 minutes. The filter can have a smaller filter constant, but the results for the estimation is almost the same and therefore it is not necessary to take more samples.

In Figure 4.9 the estimations are done with three different filter constants for a leakage size of about 1 litre/minute. The largest constant is μ_{101} and the smallest constant is μ_{103}. The relative size between the parameters is the same as for μ_1, μ_2 and μ_3. It can be seen that the largest constant gives an oscillating estimation and therefore an inaccurate value of the estimated area. The parameter μ_{101} and μ_{102} give almost the same results after 3000 seconds. The main difference is that the parameter μ_{102} has a shorter settling time.

In Figure 4.10, same parameters are used for a leakage of the size 10 litre/minute. Also for the larger leakage the largest constant gives an oscillating estimation. The smallest constant gives a too slow detection, and the pressure has decreased below 5.5 bar before the estimation reaches its largest value, see Figure 4.11. The reason for why the time axis is different in Figure 4.9 and Figure 4.10 is that the pressure decreases faster when there is a larger leakage. The time in the figures is limited to when the pressure in the system has reached 5.5 bar. The μ_{102} parameters gives

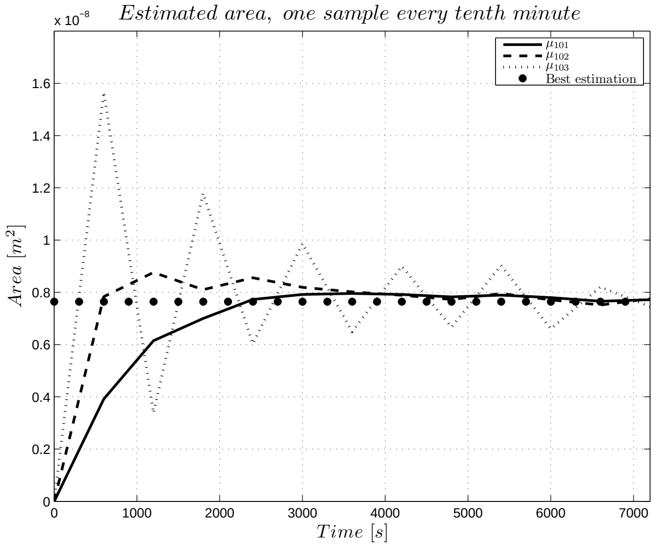

Figure 4.9. Estimated leakage area taking one sample every tenth minute. The magnitude of the leakage is around 1 litre/minute. The largest filter constant μ_{103}, gives an oscillating estimation. The smallest filter constant μ_{101}, seems to give a stable estimation but takes long time to reach its final value. The medium size of the filter parameter μ_{102}, gives a fast estimation with only small oscillations.

a relatively fast and stable estimation of the leakage area.

4.2.3 Sampling once every hour

Having a longer sampling time than one sample every minute has a big problem with the fact that the estimation time cannot be much longer than 1 hour. A too slow sample rate gives only a few or maybe no samples at all, except from the first sample, before the circuits starts isolating, see Figure 4.11.

4.3 CUSUM implementation

In order to be less sensitive to noise the CUSUM Algorithm in Section 2.2.3 is applied to the LMS estimation. A simple residual is created by taking the difference between the maximum allowed value of the estimated area and the value of the LMS estimation

$$r(t) = \hat{A}(t) - A_{limit}. \tag{4.5}$$

The residual $r(t)$ in (4.5) is used as the signal s(t) in (2.15), resulting in

$$T(t) = max\left(0, T(t-1) + r(t) - \nu\right).$$

If the test quantity T(t) is larger than a fixed threshold J, an alarm is set. The design parameter ν is set to zero as standard. In a normal fault free case the

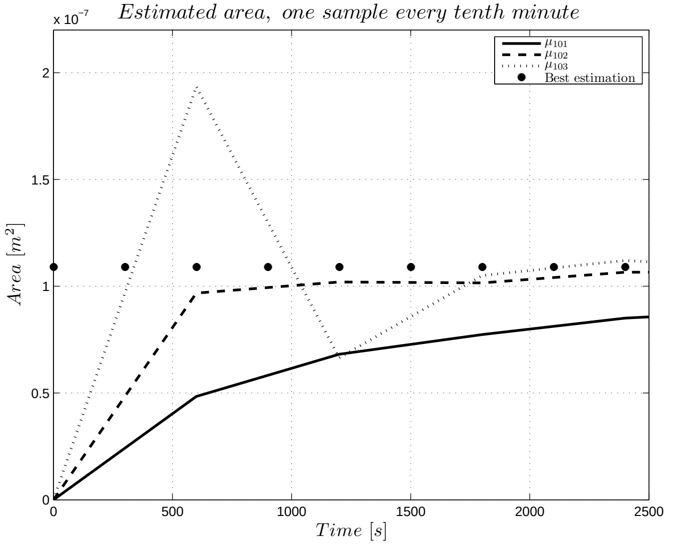

Figure 4.10. Estimated leakage area taking one sample every tenth minute. The magnitude of the leakage is around 10 litre/minute. The largest filter constant μ_{103}, gives also for larger leakages an oscillating estimation. The smallest filter constant μ_{101}, gives a too long settling time and therefore the estimation does not reach its final value before the pressure becomes too low. The medium size parameter μ_{102}, gives the best estimation and is therefore preferred.

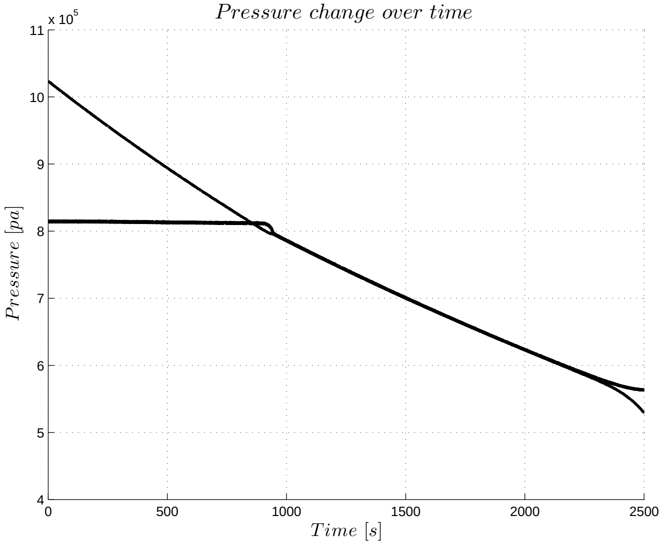

Figure 4.11. Pressure drop for a truck with an implemented leakage with the size of about 10 litre/minute. The pressure has decreased to 8 bar after 1000 seconds and the circuits starts isolating after 2500 seconds. The slowest filter constant that can be used must reach its final value within 2500 seconds to give the correct result. To be able to do the isolation between the high and low pressure circuits the first estimation must be within the first 800 seconds.

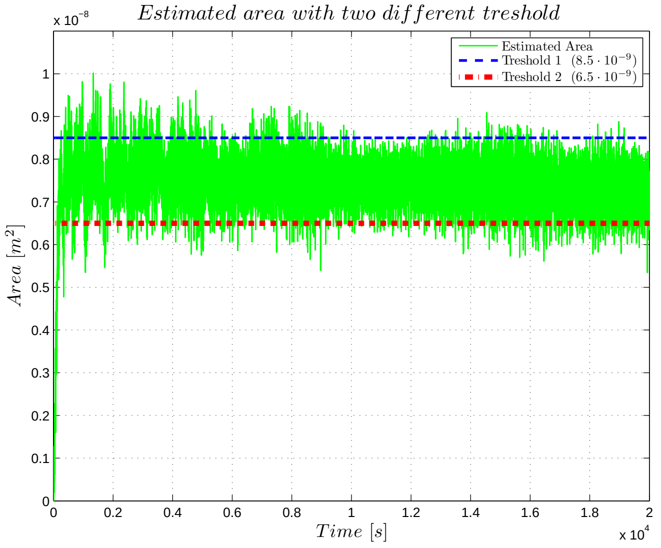

Figure 4.12. Estimated leakage area and two different possible thresholds. The estimation is most of the time over the lower threshold but under the higher threshold. If the lower threshold is used it is desired that the alarm is set since the estimated area in general is above the threshold. If the higher threshold is used the alarm should not be given since the estimation in general is below the threshold.

estimated area is less than the maximum allowed area and the residual $r(t)$ will be negative. This makes the test quantity zero.

Figure 4.12 shows how the measurement noise exceeds one of the thresholds but it is possible to see that the mean value actually is below the threshold. For the lower threshold the estimated area is larger than the threshold in average. The estimation exceeds the threshold most of the time but not all the time. In order to set the alarm for the lower threshold but not for the higher, it is not possible to use a strategy that demands that all measurements should be either over or under the threshold for setting or not setting the alarm. The results from using the estimated area with the CUSUM algorithm, after creating a residual as the difference between the estimated area and the threshold, are shown in Figure 4.13 for the higher threshold and in Figure 4.14 for the lower threshold. The results show clearly that the CUSUM implementation leads to an alarm for the lower threshold but not for the higher.

4.4 Isolation

The isolation algorithm starts at predicted time when the circuits are expected to be isolated. In order to trust the results from the isolation algorithm, a control is made to ensure that the circuits are really isolated. The first thing to check is if any of the circuits with monitored pressure are at the exact same pressure. If

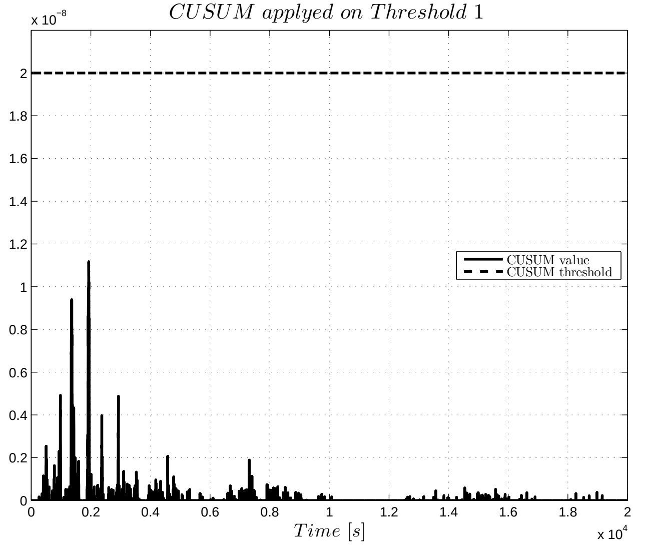

Figure 4.13. CUSUM applied to the estimated area and threshold 1 in Figure 4.12 by creating a residual as described by (4.5). Since the estimated area is lower than the threshold most of the time, the CUSUM gives the desired results with no alarm since the CUSUM threshold is not exceeded.

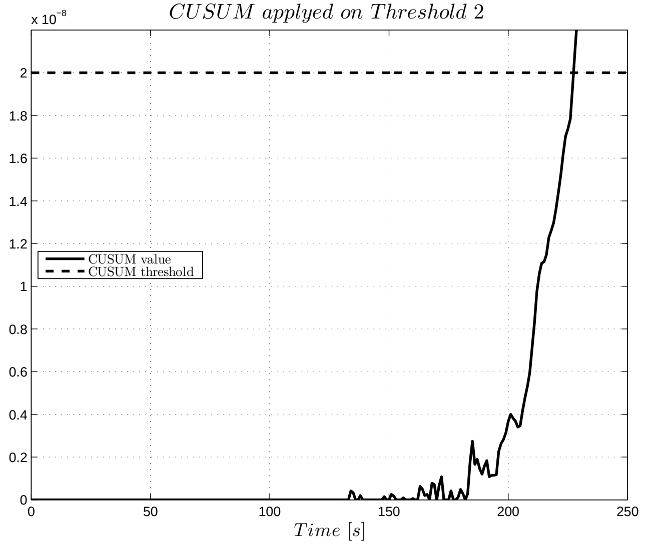

Figure 4.14. CUSUM applied to the estimated area and threshold 2 in Figure 4.12 by creating a residual as described by (4.5). Since the estimated area is larger than the threshold most of the time, the CUSUM gives the desired results with an alarm since the CUSUM gets larger over time and the CUSUM threshold in this example is exceeded after a short period of time.

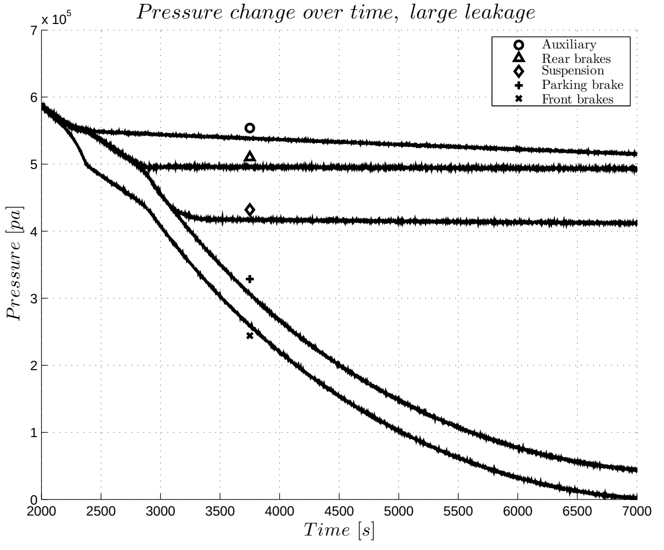

Figure 4.15. Pressure drop for a truck with a large leakage in the front brake circuit. The parking brake circuit also loses pressure because the connection with the front brake circuit via a bypass bleed.

any circuits have the same pressure as another circuit they are not isolated from each other. In the next step the leakage area is estimated for each circuit. The possibility of leaking from one circuit to another over the bypass valves must be considered in this estimation to get the correct area. If the leakage in the circuits is almost zero, the leakage can be assumed to be in one of the circuits without pressure sensors. If a leakage is detected in one of the circuits with pressure sensors, an extra investigation is made. This investigation ensures that the safety valves are closed, so the leakage not actually is in another circuit that drains air from the examined circuit. From experiments, it is discovered that safety valves are always closed when the pressure in the corresponding circuit is below 4 bar.

In Figure 4.15 the pressure drop is shown for an implemented leak in the front brake circuit. The two circuits with lowest pressure are the front brake circuit and the parking brake circuit. The reason why the pressure is decreasing in the parking brake circuit is because of the connection, by a bypass bleed, to the front brake circuit. After about 3000 seconds in Figure 4.15, the pressure in the front brake circuit has decreased below 4 bar and the statement that all safety valves should have closed seems correct. If the isolation algorithm estimates the leakages before 3000 seconds it would result in the conclusion that many circuits were leaking. Therefore the algorithm needs to wait until the pressure in the lowest circuit is below 4 bar.

If there are only the front, rear and parking brake circuits that have pressure sensors (legal requirement), and the leakage is for example in the auxiliary circuit, isolation is still possible. In Figure 4.16 a leakage is present in the auxiliary circuit.

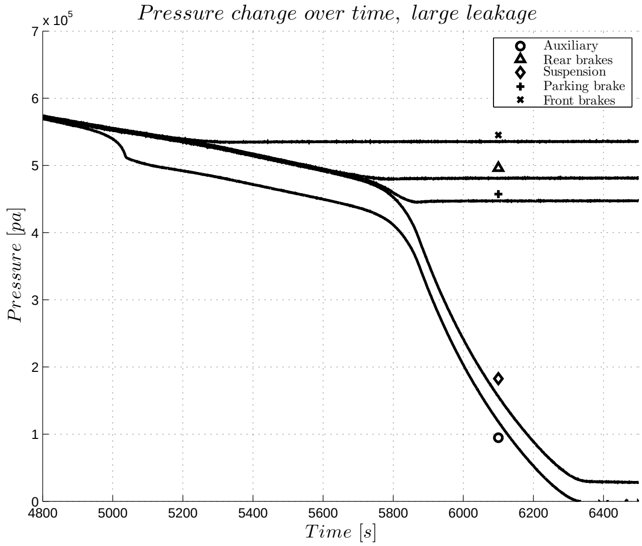

Figure 4.16. Pressure drop for a truck with a large leakage in the auxiliary circuit. The suspension circuit also loses pressure because the connection with the auxiliary circuit with bypass bleeds.

If the individual leakage area is estimated in the front, rear and parking brake circuits after 5900 seconds the results from the estimation should be a very small leakage area in those three circuits. It can be noticed that the results from the estimation should always be the same after 5900 seconds since all safety valves for the circuits with pressure sensors have closed. Therefore it is not necessary to wait until the most leaking pressure supervised circuit is below 4 bar. The result of the isolation algorithm in this case is that none of the pressure monitored circuits are leaking and the leak is either in the auxiliary circuit or in the suspension circuit. However, the auxiliary circuit is a low pressure circuit and the suspension circuit is a high pressure circuit. If the information from Section 4.1.3 is used, that is if the leakage is in a high or low pressure circuit, it is possible to say if the leakage is in the suspension (high pressure) or auxiliary (low pressure) circuit.

4.5 Decreasing leakage area

Measurements made on trucks without any implemented leakages or small leakages seem to have a very interesting behaviour. If the leakage area is estimated during the whole measurement the leakage area seems to decrease. A measurement for a truck with a small leakage implemented is showed in Figure 4.17. The leakage area in the measurements seems to decrease almost linearly when the pressure in the system decreases. One explanation for this is that the leakage area actually is larger when the pressure is high and when the pressure decreases the leakage also decreases. The implemented leakages that are used when writing this thesis are

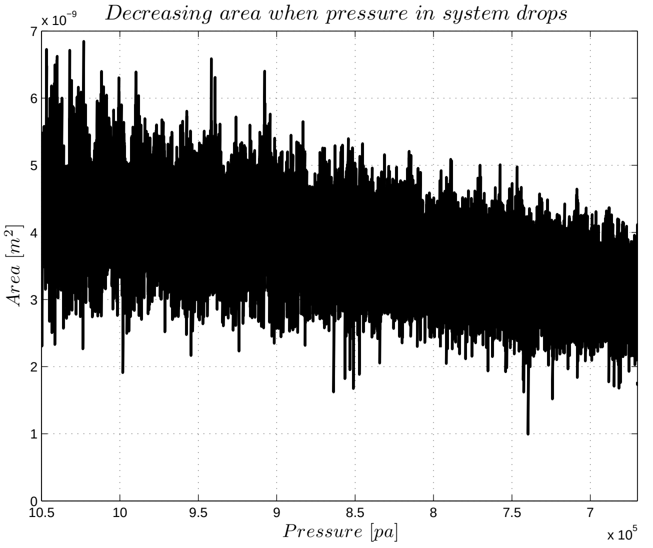

Figure 4.17. The estimated area decreases when the pressure in the system drops.

steel sockets, the leakage area is therefore constant for the implemented leakages. It can also be seen that the results from the truck with a large implemented leakage is less affected by this drift than when small or non leakage is implemented. Exactly how the leakage areas decreases and for what type of leakages when this might happen are not included in this thesis but has to be considered as an uncertainty in the measurements. A short presentation of how the decreasing leakage area can be modelled and compensated for is presented in Section 4.5.1.

4.5.1 Decreasing area model

The decreasing of the leakage area in Figure 4.17 can be modeled as proportional to the pressure. The slope, k, of the area estimation depending on the pressure can be calculated as

$$k = \frac{\Delta A}{\Delta p}$$

where ΔA and Δp is the difference in area and pressure at the start and end point in Figure 4.17. In Figure 4.4 a larger leakage is implemented on the same truck as in Figure 4.17. If the decreasing area is compensated for, the estimated area is not decreasing when the pressure is decreasing, see Figure 4.18. The model that is used to calculate the compensated area, $\hat{\hat{A}}(t)$, in Figure 4.18 is

$$\hat{\hat{A}}(t) = \hat{A}(t) + k(p(0) - p(t)),$$

where $p(0)$ is the pressure when the estimation starts and $p(t)$ the pressure at time t.

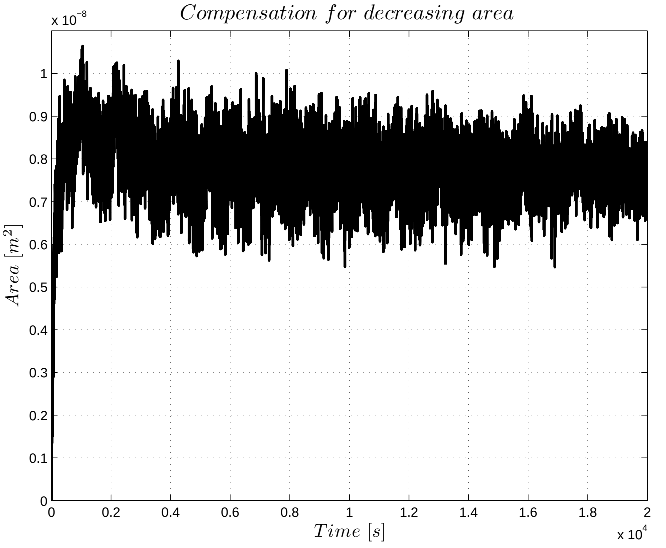

Figure 4.18. The estimated leakage area with compensation for decreasing area when the pressure in the system drops. The same estimation without compensation is shown in Figure 4.4.

The conclusion from comparing Figure 4.4 and Figure 4.18 is that the compensation is making the area more constant independent on the pressure in the system. In this example the compensation is made so that the area showed in the figures is the leakage area when the pressure in the system is high. The advantage with this is that the maximum leakage area would be given even if the estimation is done at a lower pressure. Another advantage is that the isolation performance becomes better because the total area would always be the same. The isolation algorithm compares the estimated area for the three circuits with pressure sensors to the total leakage area that is estimated before the circuits isolate. If the total leakage area has changed, the isolation algorithm might incorrect point out one of the circuits without pressure sensors as the most leaking circuit.

4.6 APS sensors

The APS has three pressure sensors and one temperature sensor. If the diagnosis algorithm is implemented it would be on the APS control unit and the data would be collected from the sensors that are attached to the APS. The performance of the sensors will limit the sampling period and the possibility to detect if the pressure is in the high or low pressure circuit.

The APS unit is connected to the Controller Area Network, CAN, on the truck. The value of the pressure and temperature sensors can be collected from CAN. Those signals are however not coming directly from the sensors. The signals are only given in discrete steps and have therefore the shape of a step function, see

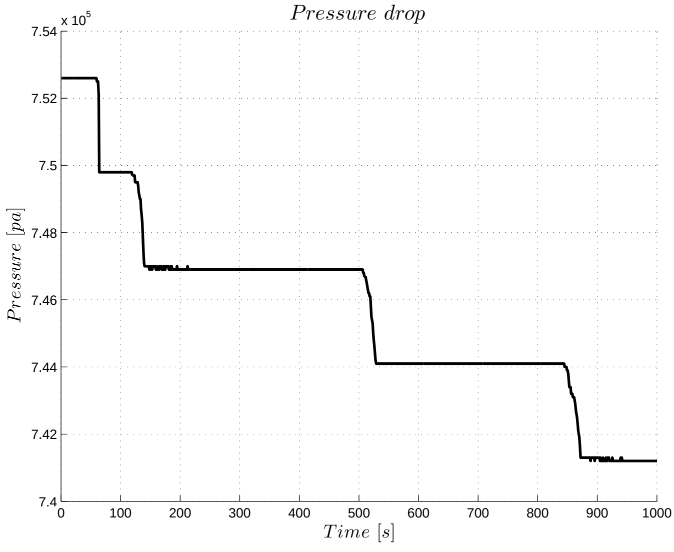

Figure 4.19. Pressure on CAN given by pressure sensors on the APS. The signal is limited to discrete levels which gives a signal with the shape of a step function.

Figure 4.19. If these signals are used with the fast sample strategy the results will either be zeros since the value is not changing or very large when the step in the signal happens. For this signal the sampling strategy, with at least spreading the samples to one sample every tenth minute, is preferred. Figure 4.20 shows the estimation of the leakage area using the strategy by sampling every second and sampling once every tenth minute. It can be seen that the estimation becomes very inaccurate when using the APS pressure sensors and sampling fast. The reason for this is that the change in the signal is zero during most of the time except from the steps in the signal when the pressure change is very large. When the samples are more spread, the step characteristic of the signal has less influence on the results.

However, if the algorithm is implemented, there are probably better signals from the sensors that can be used. Therefore the results from using the APS sensors are not very useful.

The temperature sensor on the APS unit is used for supervising the temperature of the regeneration valve which risks freezing if the surrounding temperature is too low. Since the temperature sensor on the APS is not placed directly at the regeneration valve, it calculates the temperature of the valve from the measured temperature. One idea to supervise the temperature in the pressure tanks is to use the temperature sensor on the APS. The temperature given by the APS temperature sensor, the calculated valve temperature, and the mean temperature given by external sensors rigged in the pressure tanks are shown in Figure 4.21. It is possible to see that the temperature given by the APS temperature sensor has the same behaviour besides an offset. Therefore the APS temperature sensor could

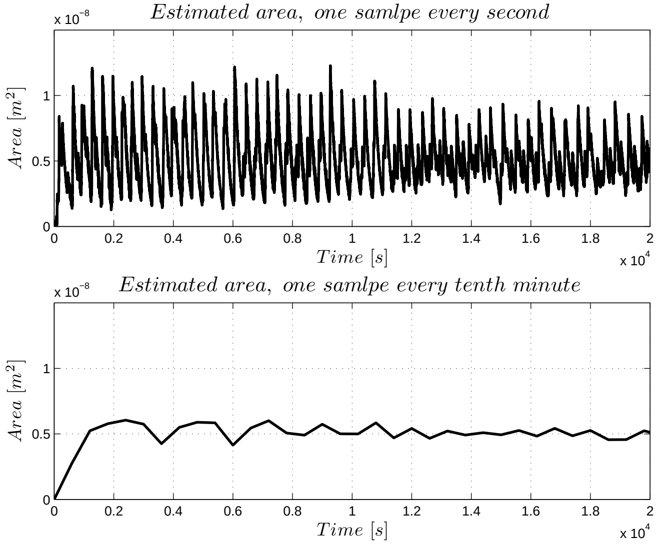

Figure 4.20. Estimated leakage area using the pressure sensors of the APS. The estimation on the top is from using a sample time of 1Hz which gives large spikes every time the signal in Figure 4.19 makes a step. The estimation below is made with the same signal but with taking one sample every tenth minute. By spreading out the samples the spikes in the estimation is decreased.

be used as an approximation of the temperature in the tanks instead of putting sensors in every tank. The possibility however of one tank getting a higher temperature is not very unlikely since some of the tanks in some vehicle configurations are positioned for direct sunlight, which the APS never will be. The CAN temperature value is unfortunately suffering the same problems as the pressure sensors, making use of the signal more difficult. However instead of using the temperature given by the APS, the surrounding temperature is more useful, see Figure 3.2.

4.7 Conclusions for diagnosis algorithm

There are several aspects that need to be considered when choosing the parameter values for the algorithm. A small μ for the LMS filter makes the estimation containing less noise but makes the estimation to take longer time and will therefore also use more energy. There is also a risk with a too small μ, that the filter not reaches its largest value before the circuits start isolating. The main focus used in this thesis however, when choosing parameters, is to get full isolation. To get full isolation, the isolation between high and low pressure circuits must be obtained by making two estimations as described in Section 4.1.3. To be able to do the isolation, the LMS estimation must be fast enough. Therefore the sampling frequency should be 1 Hz and the parameter should be the size of μ_2, see Table 4.1, in order to make the estimation fast enough. Because both μ_1 and μ_2 give a filter

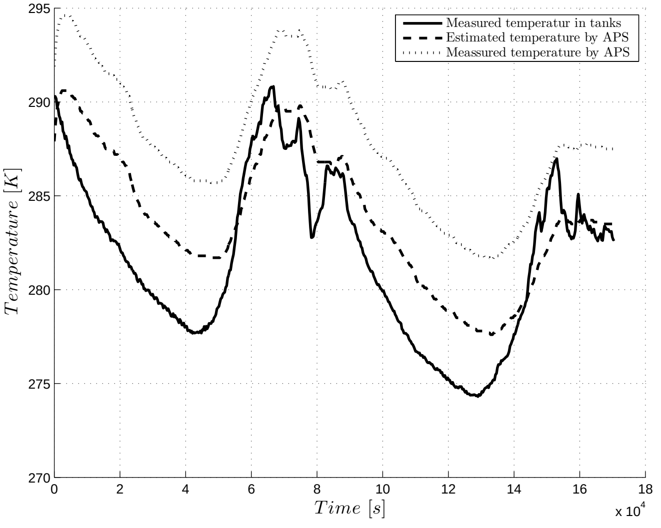

Figure 4.21. Temperature measured with sensors in pressure tanks, temperature sensor on APS and estimated temperature for the regeneration valve.

that is fast enough, to use for isolation between high and low pressure circuits, μ_2 is preferred since it gives a more accurate estimation for smaller leakages. Using μ_3, or spreading out the samples to one sample every tenth minute makes the estimations take too long time and therefore the risk of not being able to get full isolations for larger leakages is more likely.

The sensors on the APS can probably be used in an implementation of the algorithm if there is a better signal available than the signal that exist on the CAN.

In the validation in Section 5, μ_2 from Section 4.2.1 is used together with external sensors since the APS sensor signals on CAN are not good enough.

Chapter 5

Validation

When designing the diagnosis algorithm, one important design parameter is which and how good performances are needed. How small leakages are needed to be detected and how large inaccuracy is accepted? The main reason for detecting leakages in the air pressure system is to reduce the fuel consumption. While driving, a leak in the system will make the compressor work more often and therefore use more energy from the engine. In order to save fuel, the sizes of leakages that need to be detected are approximately 10 litres/minute. A leakage of this size, gives an increased fuel consumption of about 0.1-0.2%, see Section 3.3.1.

There is also another factor that can be interesting to study, to get an idea of how big a leakage is supposed to be, before it is worth even consider it as a leakage. When an air leaking heavy truck is parked over the night or for a lunch stop, the pressure in the circuits might decrease because of a leakage. An annoying thing for the driver is if the pressure has decreased so much that the driver must wait when starting the vehicle, before there is enough pressure to release the parking brake. From a driver's perspective, it is necessary to repair the leak when these situations occur. The size of the leakage when this starts to be a problem is 1 litre/minute.

The filter parameter μ that is recommended and used for validation in this thesis, is tuned to detect leakages of the size of 1 litre/minute or larger and at the same time be able to get full isolation performance even for leakages at the size of 10 litres/minute.

5.1 Validation by measurements

The validation is done with measurements from a real truck. The validation data has not been used when tuning the design parameters for the filter. Five different tests with four different implemented leakages will be used; the fifth test is from a truck without any implemented leakage. The corresponding pressure drops to the validation data can be found in Appendix A. Since it is difficult to exactly know the real effective leakage area of the implemented leakages there is no perfect reference. However, the leakages that have been implemented during the tests are the same leakages that have been used during the development of the algorithm, except one leakage which have not been used before. From the tests performed during the development, the mean value for each test is calculated, called best estimation. Therefore the expected estimated leakage area is known. If the results from the tests are the same value as expected this indicates that the algorithm works well. If the results from the tests are different from what is expected, or if the estimations of the leakage area are drifting more than expected or oscillating a lot, this indicates that the algorithm is not working. The isolation performance is easier to evaluate. If the algorithm isolates the leakage to the correct circuit the algorithm is working. The expected results for the four different tests are shown in Table 5.1. The leakage that not has been used before has an unknown leakage area. The threshold that will be used is set to the size of 1 litre/minute which corresponds to a leakage area of $8.5 \cdot 10^{-9}$ m^2. If the diagnosis algorithm is working correctly, implemented leakages would trigger the alarm and the right circuit should be isolated.

Table 5.1. Expected results from the validation test.

Test	Expected leakage size [m^2]
NO leakage	$< 4 \cdot 10^{-9}$
Leakage 1	$1.6 \cdot 10^{-8}$
Leakage 2	$7.1 \cdot 10^{-8}$
Leakage 3	$1.1 \cdot 10^{-7}$

5.2 Results

The results from the validation data are presented with the estimated area and the isolation results from the algorithm. The expected result, where it exists, for the leakage area is marked in the same figures as the estimated area for every test. The leakages are named: Leakage 1-3 for the leakages that have been used before and the leakage which have not been used before is named "Unknown leakage". To see how well the estimated area and the model describes the pressure change in the system, the pressure is simulated using the second estimation, A_2, and the temperature.

5.2.1 No implemented leakage

The first test is with no implemented leakage. The estimated leakage area is shown in Figure 5.1. It can be seen that the leakage area is always below $8.5 \cdot 10^{-9}$ m^2, so the alarm is not triggered. There are some uncertainties in the estimation which can be seen as the variations in the estimations. The leakage is however very small and the exact size is not very important as long as the leakage is clearly below the smallest threshold.

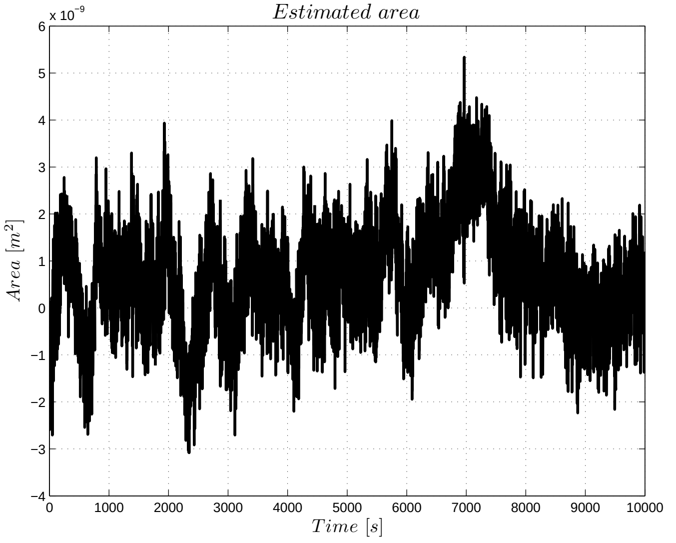

Figure 5.1. Estimated leakage area without any implemented leakage. The estimated leakage area is always below the threshold value of $8.5 \cdot 10^{-9}$ m^2 which is the size of a 1 litre/minute leakage.

5.2.2 Leakage 1

Leakage 1 is the smallest implemented leakage that is used. The leakage is implemented in the auxiliary circuit which is a low pressure circuit. The estimated leakage area together with the expected results are shown in Figure 5.2. The estimated leakage area is close to the expected results which is a good result. The reason for why the estimation and expectation are not the same in the beginning of the estimation is that the leakage is implemented in a low pressure circuit but the algorithm has been using the pressure for the high pressure circuits in the estimation. The isolation results for isolation between high or low pressure circuit is shown in Table 5.2. The ratio between the second and first estimation is larger than the threshold and therefore the leakage is estimated to be in a low pressure circuit since the high pressure has been used in the estimations. The second estimation is close to the expected value $A^{\star}$ which indicates that the estimation is good.

The isolation results from after that the circuits have divided is given by Table 5.3. All three circuits with pressure sensors have a very small leakage area. Therefore the leakage must be in one of the two circuits without pressure sensor. But since the auxiliary circuit is a low pressure circuit and the suspension circuit is a high pressure circuit the leakage can be isolated to be in the auxiliary circuit.

The results from simulating the pressure drop, using A_2 in Table 5.2 and the temperature as input data, is shown in Figure 5.3. The simulated pressure drop

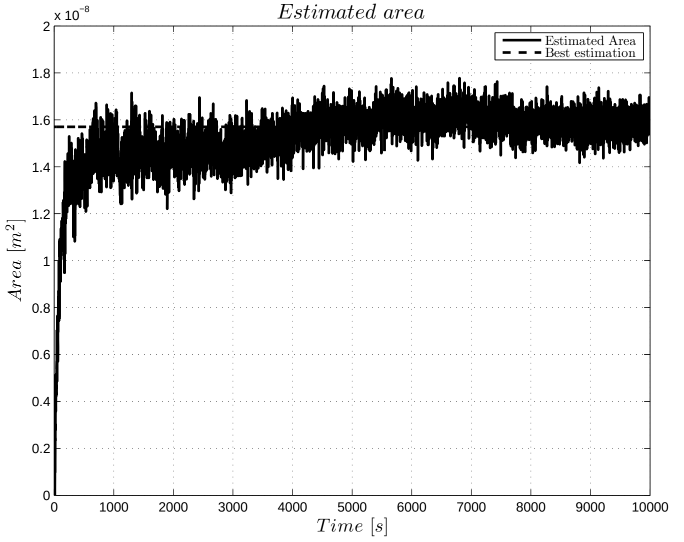

Figure 5.2. Estimated leakage area with implemented leakage and expected result, Leakage 1. A small drift can be seen in the estimation. The drift in this case indicates that the leakage is in a low pressure circuit, since the pressure in the high pressure circuits has been used in the estimation. The drift stops after 6000 seconds since the pressure in the high pressure circuits have decreased below 8 bar.

Table 5.2. Results for isolation between high or low pressure circuit, Leakage 1. The pressure used in the first estimation, A_1, is the pressure in the high pressure circuits. The ratio between the second estimation, A_2, and the first estimation is larger than the threshold, $J_{high/low}$, and therefore the leakage must be in a low pressure circuit. The value of the second estimation is close to the expected leakage area, $A^{\star}$, which is a good result.

A_1	A_2	$A^{\star}$	$\frac{A_2}{A_1}$	$J_{high/low}$	Location	Estimated location
$1.40 \cdot 10^{-8}$	$1.58 \cdot 10^{-8}$	$1.57 \cdot 10^{-9}$	1.13	1.08	Low	Low

Table 5.3. Results from isolation algorithm, Leakage 1. The estimated areas are low for the three circuits with pressure sensors. The leakage must therefore be in either the auxiliary circuit or the suspension circuit.

A_{front}	A_{rear}	A_{park}	$A_{auxilliary\ and\ suspension}$
$3.12 \cdot 10^{-10}$	$-3.67 \cdot 10^{-10}$	$-2.84 \cdot 10^{-11}$	$1.56 \cdot 10^{-8}$

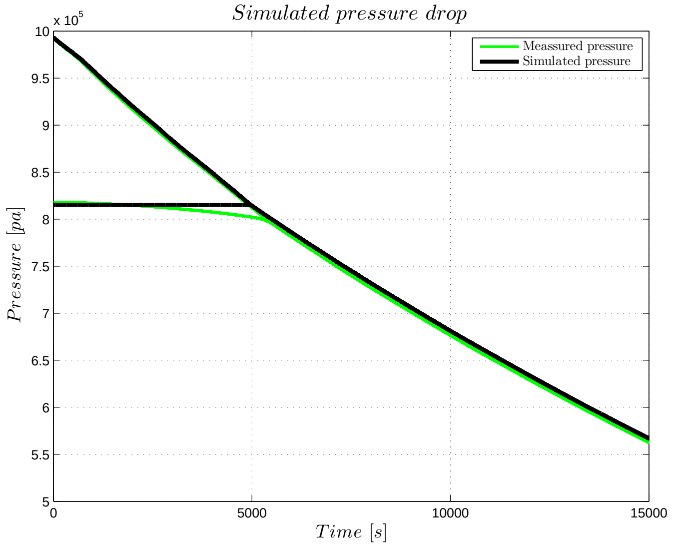

Figure 5.3. Simulated pressure drop using the estimated area, Leakage 1. The simulated pressure drop is close to the measurements which indicate that the model and estimation of the leakage area are good.

is almost identical with the measured pressure; this indicates that the model with a well estimated leakage area describes the pressure change in the system good.

5.2.3 Leakage 2

Leakage 2 is larger than leakage 1 and is implemented in the suspension circuit. The estimated leakage area, together with the expected result is shown in Figure 5.4. The estimated area is stable but is slightly below the expected result. The reason for this could be explained by that the leakage has been a little deformed. The last test before the validation did also indicate that the leakage area was a little smaller than the measurements done before. Since the leakage area is small the hole might have been clogged with a small scrap.

The isolation results for isolation between high or low pressure circuit are shown in Table 5.4. The ratio between the second and the first estimation is smaller than the threshold and therefore the leakage is estimated to be in a high pressure circuit, which is correct.

The isolation algorithm points out the leakage to be in either the auxiliary or the suspension circuit, see Table 5.5. But since the auxiliary circuit is a low pressure circuit and the suspension circuit is a high pressure circuit the leakage can be isolated to be in the suspension circuit.

The results from simulating the pressure drop, using A_2 in Table 5.4 end the temperature as input data, is shown in Figure 5.5. The simulation gives a pressure

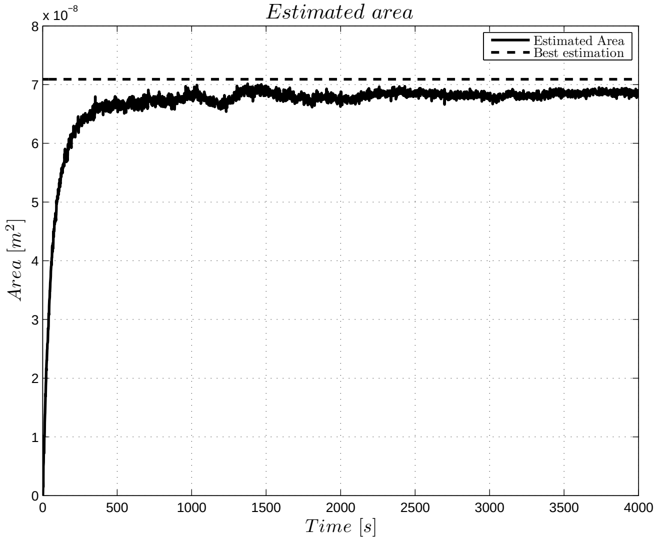

Figure 5.4. Estimated leakage area with implemented leakage and expected result, Leakage 2. The estimation is below the expected value which tells that the leakage seems to give a little less air leakage than expected.

Table 5.4. Results for isolation between high or low pressure circuit, Leakage 2. The pressure used in the first estimation, A_1, is the pressure in the high pressure circuits. The ratio between the second estimation, A_2, and the first estimation is smaller than the threshold, $J_{high/low}$, and therefore the leakage must be in a high pressure circuit. The estimated area in both the estimations is a little lower than the expected area, $A^{\star}$.

A_1	A_2	$A^{\star}$	$\frac{A_2}{A_1}$	$J_{high/low}$	Location	Estimated location
$6.66 \cdot 10^{-8}$	$6.56 \cdot 10^{-8}$	$7.1 \cdot 10^{-8}$	0.98	1.04	High	High

Table 5.5. Results from the isolation algorithm, Leakage 2. The estimated leakage area for the three circuits with pressure sensors is low. The leakage must therefore be in the auxiliary circuit or the suspension circuit.

A_{front}	A_{rear}	A_{park}	$A_{auxilliary\ and\ suspension}$
$8.95 \cdot 10^{-10}$	$1.73 \cdot 10^{-10}$	$3.29 \cdot 10^{-11}$	$6.45 \cdot 10^{-8}$

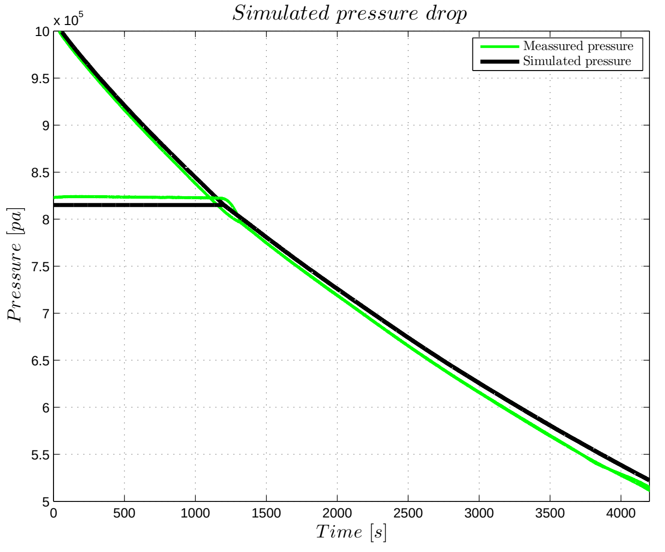

Figure 5.5. Simulated pressure drop using the estimated area, Leakage 2. The simulated pressure drop is a little slower than the measured pressure. One explanation is that the estimated leakage area is a little too small.

Table 5.6. Results for isolation between high or low pressure circuit, Leakage 3. The pressure used in the first estimation, A_1, is the pressure in the high pressure circuits. The ratio between the second estimation, A_2, and the first estimation is smaller than the threshold, $J_{high/low}$, and therefore the leakage must be in a high pressure circuit. The threshold is very low since there is almost no pressure difference between the high and low pressure circuits when the first estimation is complete. A small error in one of the estimations could have lead to an incorrect localisation of the leakage.

A_1	A_2	$A^\star$	$\frac{A_2}{A_1}$	$J_{high/low}$	Location	Estimated location
$1.07 \cdot 10^{-7}$	$1.04 \cdot 10^{-7}$	$1.08 \cdot 10^{-7}$	0.98	1.02	High	High

drop which is a little too slow. The fault is traced to come from a too small filter constant μ. The filter almost reaches its final value but not completely in the second estimation. If the first estimated area, A_1, is used instead, it is almost a perfect match between simulation and measurements, see Figure 5.6.

5.2.4 Leakage 3

Leakage 3 is the largest leakage that has been used during the development of the algorithm. The leakage is implemented in the front brake circuit. The estimated leakage area together with the expected results is shown in Figure 5.7. The estimated area is close to the expected result which indicates a good estimation.

The algorithm succeeds to correctly isolate the leakage to one of the high pressure circuits, see Table 5.6. However, the threshold, $J_{high/low}$, is low which indicates

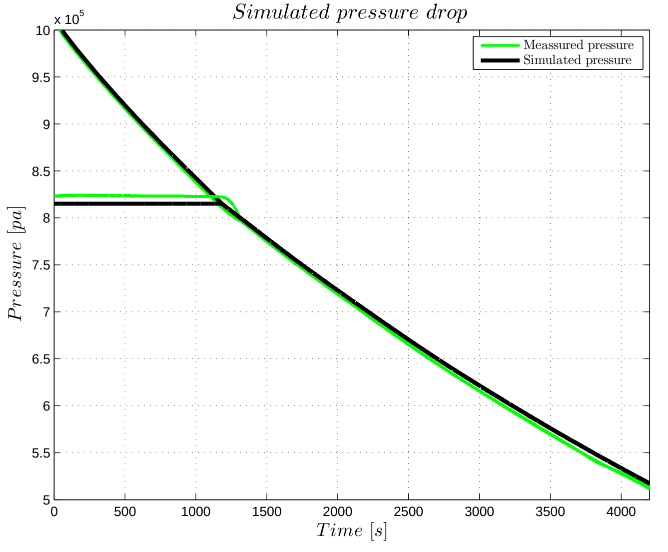

Figure 5.6. Simulated pressure drop using the estimated area from the first estimation A_1, Leakage 2. The simulated pressure drop is almost identical with the measurements. This indicates that A_1 is a better estimation of the leakage area than A_2, see Figure 5.5.

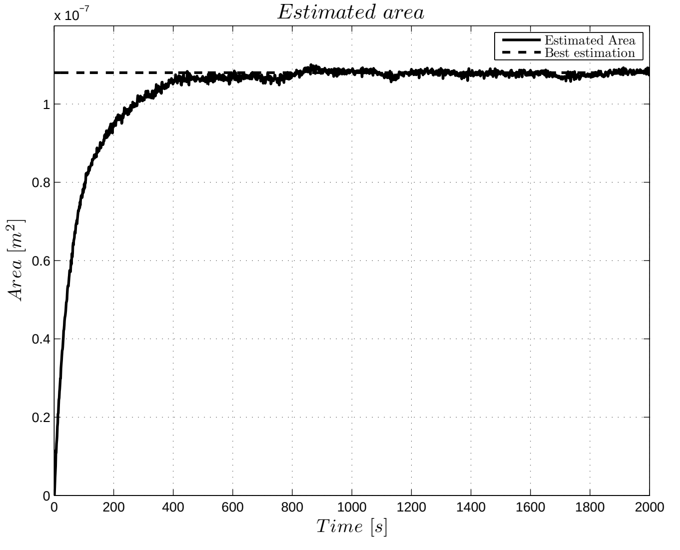

Figure 5.7. Estimated leakage area with implemented leakage and expected result, Leakage 3. The estimation is very close to the expected result which indicates that the estimation algorithm is good.

Table 5.7. Results from the isolation algorithm, Leakage 3. The results show clearly that the leakage is in the front brake circuit.

A_{front}	A_{rear}	A_{park}	$A_{auxilliary\ and\ suspension}$
$1.03 \cdot 10^{-7}$	$2.55 \cdot 10^{-10}$	0	$1.03 \cdot 10^{-9}$

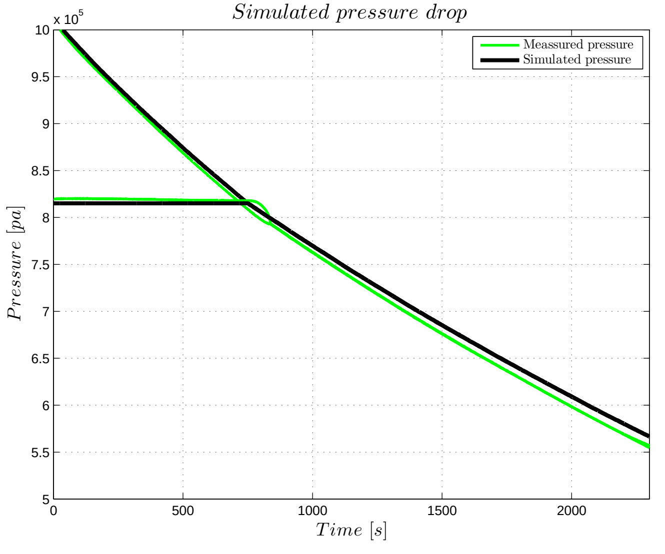

Figure 5.8. Simulated pressure drop using the estimated area, Leakage 3. The simulated pressure drop is a little slower than the measurements. The reason can be that the estimated area is a little too small.

that the pressure difference between the high and low pressure circuits was almost zero when the first estimation finished. A little lower initial pressure or a larger leakage would probably result in a missed isolation. The isolation results from after that the circuits have divided is given by Table 5.7. The isolation algorithm points out the leakage to be in rear brake circuit which is the correct circuit.

The results from simulating the pressure drop, using A_2 in Table 5.6 and the temperature as input data, is shown in Figure 5.8. The result from the simulation is similar to the results for Leakage 2 in 5.2.3. The reason for the difference between simulation and measurements is the same as for Leakage 2, because of a little too small μ.

5.2.5 Unknown leakage

An unknown leakage is used to test if the estimation algorithm also works for other leakages than the one that is used during the development of the algorithm. The position of the leakage is the rear break circuit. The estimated leakage area is shown in Figure 5.9. The estimated area is stable which indicates a good estimation.

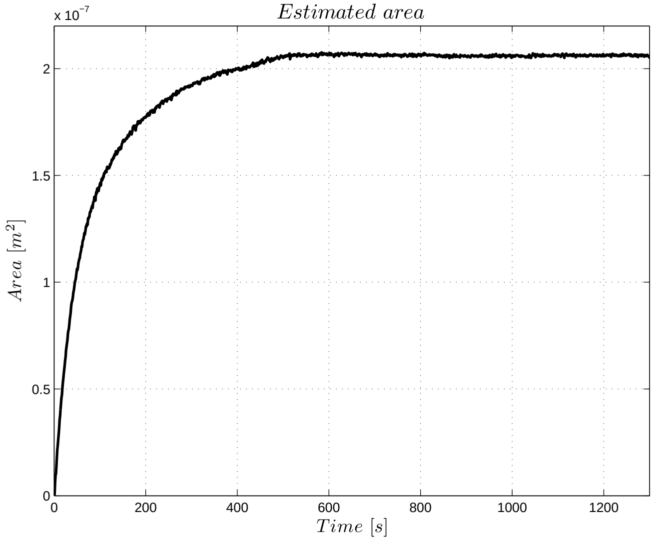

Figure 5.9. Estimated leakage area with implemented leakage and expected result, Unknown leakage. The estimation is stable after the settling time and does not have any oscillations or drift.

Table 5.8. Results for isolation between high and low pressure circuit, Unknown leakage. Since the leakage is large, the pressure is dropping fast and the filter is too slow to finish the first estimation before the pressure in the high pressure circuits has got below 8 bar. Isolation between the high and low pressure circuit is therefore not possible.

A_1	A_2	$A^\star$	$\frac{A_2}{A_1}$	$J_{high/low}$	Location	Estimated location
$2.03 \cdot 10^{-7}$	-	-	-	-	High	-

Table 5.9. Results from the isolation algorithm, Unknown leakage. The results shows that the leakage is in the rear brake circuit.

A_{front}	A_{rear}	A_{park}	$A_{auxilliary\ and\ suspension}$
$3.83 \cdot 10^{-11}$	$2.06 \cdot 10^{-7}$	$-3.82 \cdot 10^{-11}$	$-3.62 \cdot 10^{-9}$

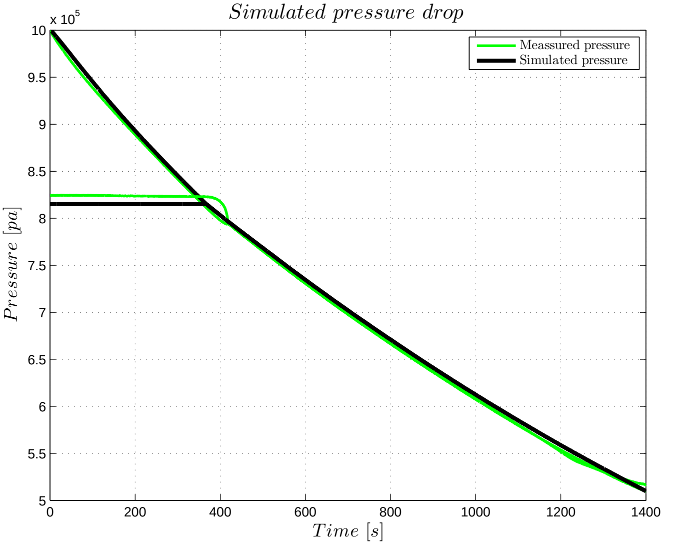

Figure 5.10. Simulated pressure drop using the estimated area, Unknown leakage. The simulated pressure drop is similar to the measured pressure. This shows that the model and estimation of the area works good also for a little larger leakages.

The algorithm does not however succeed to correctly isolate the leakage to one of the high pressure circuits, see Table 5.8. The leakage is too large and the pressure in the high pressure circuit has reached the same pressure as the low pressure circuit before the first estimation is completed. The isolation results from after that the circuits has divided is given by Table 5.9.

The isolation algorithm points out the leakage to be in the front brake circuit which is the correct circuit. Because the leakage is in a circuit with a pressure sensor it is possible to isolate the leakage. If the leakage have been in one of the two circuits without pressure sensor it would not be plausible to isolate it from the other circuit that have no pressure sensor.

The results from simulating the pressure drop, using A_1 in Table 5.8 and the temperature is shown in Figure 5.10. The reason for why the simulation does not have the same problem as Leakage 2 and Leakage 3, is that the Unknown leakage was too large in order to do the isolation between high and low pressure circuits. Therefore no second estimation, A_2, was done and A_1 is used for the simulation.

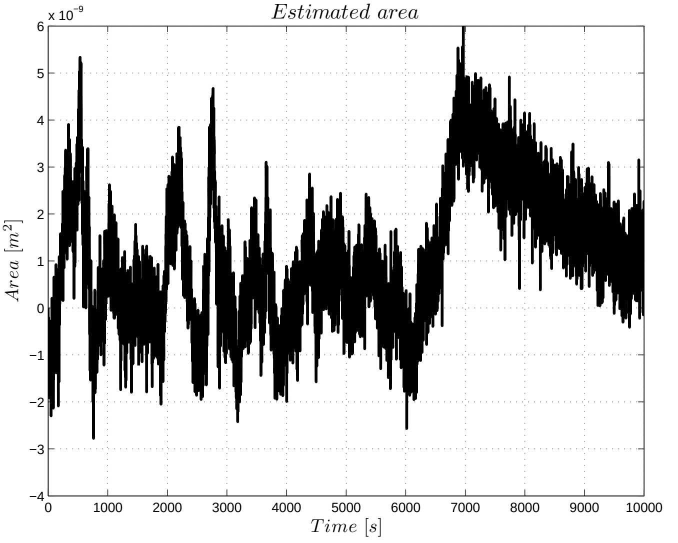

Figure 5.11. Estimated leakage area, using the surrounding temperature, without any implemented leakage. The estimated leakage area is always below the threshold value of $8.5 \cdot 10^{-9}$ m^2, which is the size of a 1 litre/minute leakage.

5.3 Results using surrounding temperature

The use of the surrounding temperature, instead of using temperature sensors in the tanks has been discussed in this thesis. The validation results using the surrounding temperature are presented in this Section.

5.3.1 No implemented leakage, surrounding temperature

The estimated leakage area when no leakage is implemented with the surrounding temperature as approximation for the air temperature in the tanks is shown in Figure 5.11. By comparing the result to the estimated area in Figure 5.1, it can be seen that the estimations are similar except that the spikes in the estimation is a little larger when using the surrounding temperature. The temperature in the tanks and the surrounding temperature are shown in Figure 5.12. In this case the surrounding temperature is close to the tank temperature except a small offset.

5.3.2 Leakage 1, surrounding temperature

The estimated leakage area when using the surrounding temperature is shown in Figure 5.13. It can be seen that the estimation in Figure 5.13 does not differ significantly from the estimation in Figure 5.2. The temperature in the tanks and the surrounding temperature are shown in Figure 5.14. The surrounding temperature corresponds well to the temperature in the tanks except for a small offset.

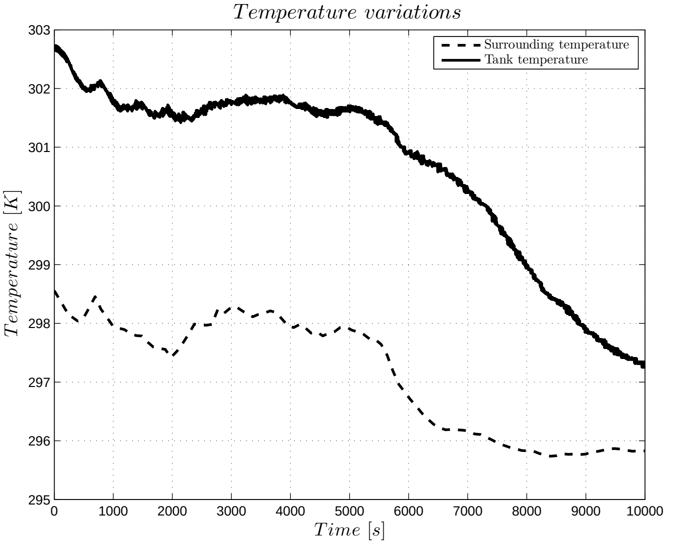

Figure 5.12. Temperature measured in the tanks compared to the surrounding temperature, for no implemented leakage. The temperatures look similar except for an offset.

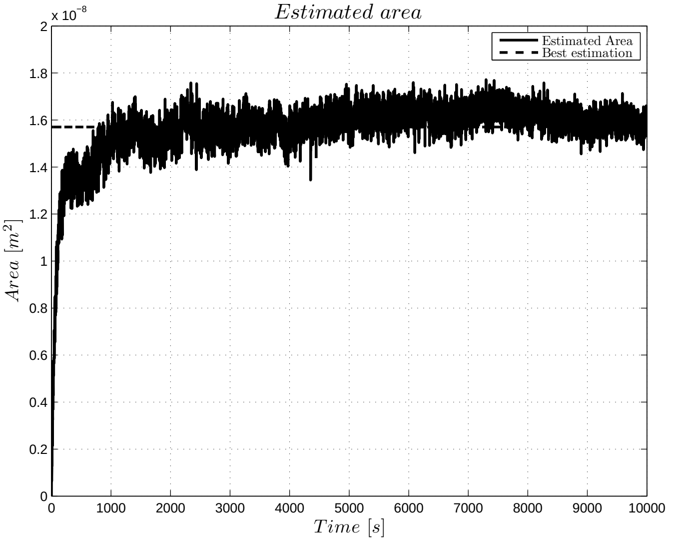

Figure 5.13. Estimated leakage area, using the surrounding temperature, for Leakage 1. The estimated area has a small positive drift because the leakage is in a low pressure circuit. The estimation is similar to the estimation in Figure 5.2.

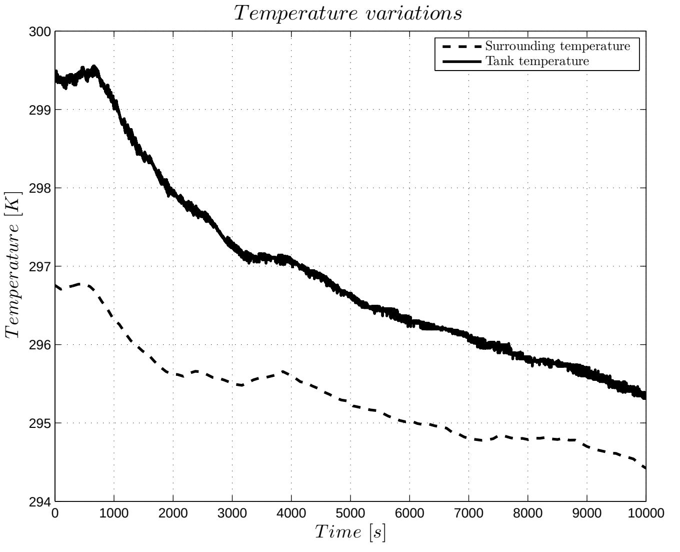

Figure 5.14. Temperature measured in the tanks compared to the surrounding temperature, for Leakage 1. The temperatures are similar except for an offset.

Table 5.10. Results for isolation between high or low pressure circuit using the surrounding temperature, Leakage 1. The pressure used in the first estimation, A_1, is the pressure in the high pressure circuits. The ratio between the second estimation, A_2, and the first estimation is larger than the threshold, $J_{high/low}$, and therefore the leakage must be in a low pressure circuit. The second estimation is close to the expected result $A^{\star}$.

A_1	A_2	$A^{\star}$	$\frac{A_2}{A_1}$	$J_{high/low}$	Location	Estimated location
$1.37 \cdot 10^{-8}$	$1.60 \cdot 10^{-8}$	$1.57 \cdot 10^{-9}$	1.18	1.08	Low	Low

The isolation results for isolation between high or low pressure circuits are shown in Table 5.10 and the isolation results from after that the circuits have divided is given in Table 5.11. It can be seen that the same isolation performance is given when the surrounding temperature is used, instead the temperature sensors in the tanks.

Table 5.11. Results from isolation algorithm using the surrounding temperature, Leakage 1. The results show that the leakage not is in one of the three circuits with pressure sensor. The leakage is either in the auxiliary circuit or the suspension circuit.

A_{front}	A_{rear}	A_{park}	$A_{auxilliary\ and\ suspension}$
$1.46 \cdot 10^{-10}$	$2.12 \cdot 10^{-11}$	$1.33 \cdot 10^{-11}$	$1.58 \cdot 10^{-8}$

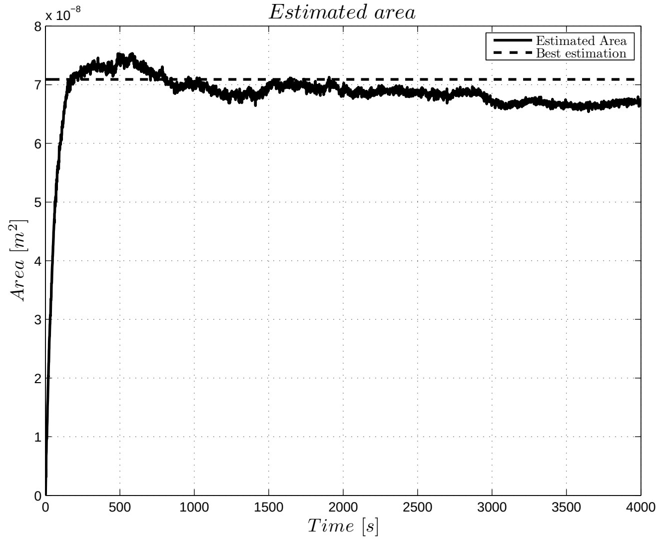

Figure 5.15. Estimated leakage area, using the surrounding temperature, for Leakage 2. There is an overshoot in the beginning in the estimations because the use of surrounding temperature as approximation of the temperature in the tanks. The estimation is close to the estimation in Figure 5.4 after 2000 seconds. This is the time for when the surrounding and tank temperature has the same value, see Figure 5.16.

5.3.3 Leakage 2, surrounding temperature

The estimated leakage area when using the surrounding temperature is shown in Figure 5.15. The estimation is in general below the expected value except in the beginning of the estimation where there is an overshoot in the estimation. The overshoot can be explained by a model fault that happens because the assumption of using the surrounding temperature as approximation of the temperature in the tanks. The temperature in the tanks and the surrounding temperature are shown in Figure 5.16. In the beginning of the measurements, the tank temperature is higher than the surrounding temperature. The temperature in the tanks is than dropping fast to the same temperature as the surrounding temperature. This temperature drop will affect the pressure in the tanks but since this is not compensated for in the estimation when using the surrounding temperature, the estimated leakage area becomes larger.

The isolation results for isolation between high or low pressure circuit is shown in Table 5.12 and the isolation results from after that the circuits have divided is given in Table 5.13. It can be seen that the same isolation performance is given when the surrounding temperature is used, as when temperature sensors in the tanks is used.

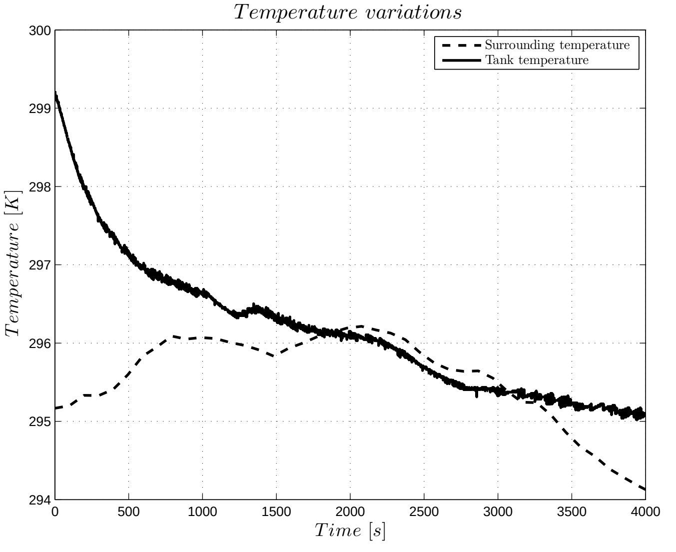

Figure 5.16. Temperature measured in the tanks compared to the surrounding temperature, for Leakage 2. The tank temperature drops during the first 2000 seconds while the surrounding temperature increases. This difference affects the result in the estimation if the tank temperature is approximated with the surrounding temperature, compare Figure 5.4 and Figure 5.15.

Table 5.12. Results for isolation between high or low pressure circuit using the surrounding temperature, Leakage 2. The overshoot in the estimation, see Figure 5.15, gives a larger value for the first estimation, A_1, than for the second estimation, A_2. Therefore the ratio between the second and first estimation becomes small. Fortunately the ratio is suppose to be below the threshold, $J_{high/low}$, in this case to get the right result. If there was an undershoot instead of an overshoot in the estimation, the results would probably have been incorrect.

A_1	A_2	$A^\star$	$\frac{A_2}{A_1}$	$J_{high/low}$	Location	Estimated location
$7.42 \cdot 10^{-8}$	$6.78 \cdot 10^{-8}$	$7.1 \cdot 10^{-8}$	0.91	1.04	High	High

Table 5.13. Results from isolation algorithm using the surrounding temperature, Leakage 2. The results show that there are no leakages in the three circuits with pressure sensors. The leakage is either in the auxiliary circuit or the suspension circuit.

A_{front}	A_{rear}	A_{park}	$A_{auxilliary\ and\ suspension}$
$5.23 \cdot 10^{-11}$	$3.24 \cdot 10^{-10}$	$-9.23 \cdot 10^{-11}$	$6.75 \cdot 10^{-8}$

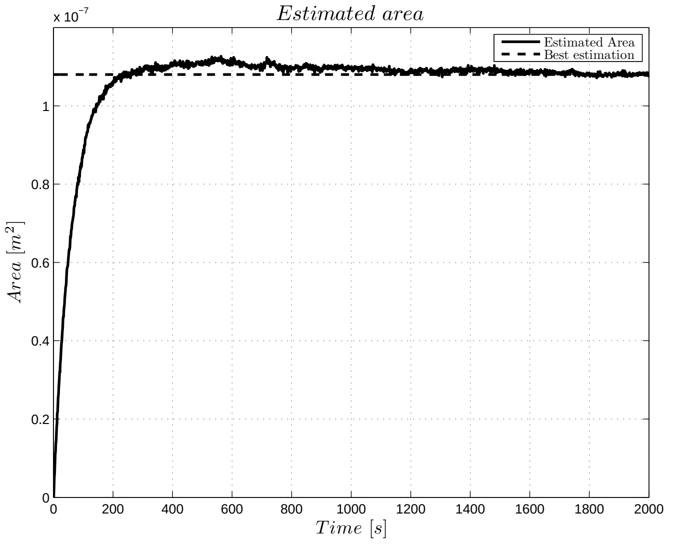

Figure 5.17. Estimated leakage area, using the surrounding temperature, for Leakage 3. There is a small overshoot in the beginning of the estimation compared to Figure 5.7. This is because the temperature in the tanks is decreasing in the beginning which the surrounding temperature does not, see Figure 5.18.

Table 5.14. Results for isolation between high or low pressure circuit using the surrounding temperature, Leakage 3. The pressure used in the first estimation, A_1, is the pressure in the high pressure circuits. The ratio between the second estimation, A_2, and the first estimation is smaller than the threshold, $J_{high/low}$, and therefore the leakage must be in a high pressure circuit.

A_1	A_2	$A^\star$	$\frac{A_2}{A_1}$	$J_{high/low}$	Location	Estimated location
$1.12 \cdot 10^{-7}$	$1.05 \cdot 10^{-7}$	$1.08 \cdot 10^{-7}$	0.94	1.02	High	High

5.3.4 Leakage 3, surrounding temperature

The estimated leakage area when using the surrounding temperature is shown in Figure 5.17. Also for this leakage there is a small overshoot in the beginning, as for Leakage 2. The explanation is also the same and the temperatures are shown in Figure 5.18.

The isolation results for isolation between high or low pressure circuit are shown by Table 5.14 and the isolation results from after that the circuits have divided is given in Table 5.15. It can be seen that the same isolation performance is given when the surrounding temperature is used instead the temperature sensors in the tanks. However, if there would have been an undershoot instead of an overshoot of the same size, the algorithm would probably give the wrong result. This is because the first estimated area A_1 would be smaller than A_2 and since the threshold is low, it would be breached.

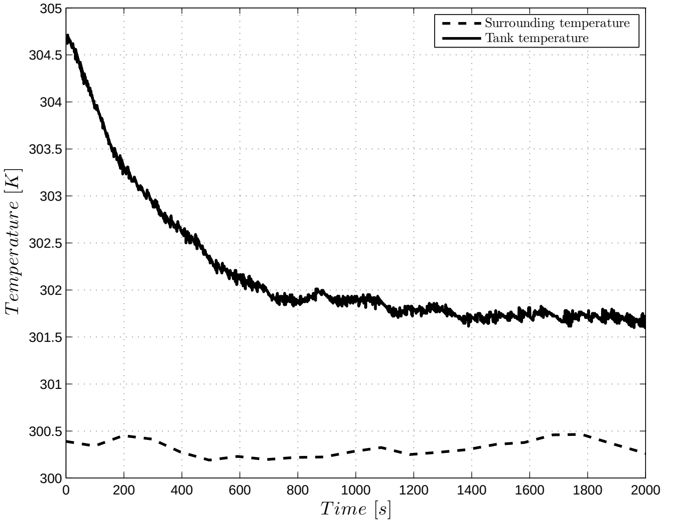

Figure 5.18. Temperature measured in the tanks compared to the surrounding temperature, for Leakage 3.

Table 5.15. Results from isolation algorithm using the surrounding temperature, Leakage 3. The results show that the leakage is in the front brake circuit.

A_{front}	A_{rear}	A_{park}	$A_{auxilliary\ and\ suspension}$
$1.03 \cdot 10^{-7}$	$-3.23 \cdot 10^{-10}$	0	$2.22 \cdot 10^{-9}$

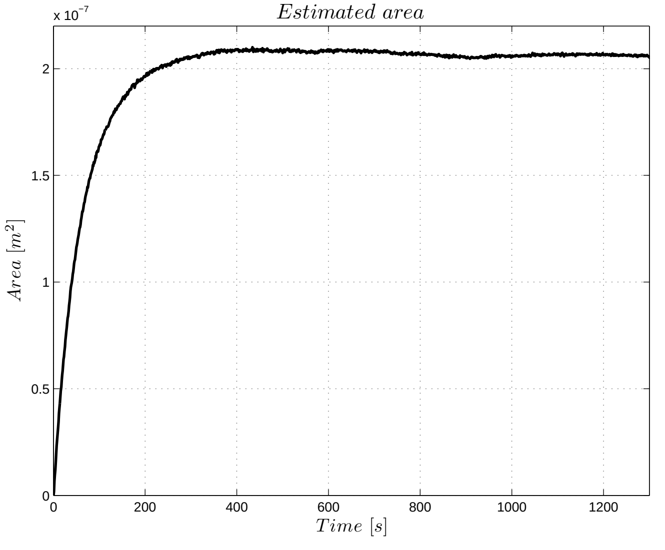

Figure 5.19. Estimated leakage area, using the surrounding temperature, for Unknown leakage. The estimation is similar to the estimation in Figure 5.9. There is a difference between the surrounding temperature and the tank temperature in the beginning of the estimation, see Figure 5.20. However, the temperatures are almost the same after 400 seconds which is when the filter has reached its maximum value.

Table 5.16. Results for isolation between high or low pressure circuit using the surrounding temperature, Unknown leakage. Since the leakage is large the pressure in the high pressure circuits has decreed below 8 bar before the first estimation is complete. Therefore the isolation between the high and low pressure circuits is not possible.

A_1	A_2	$A^\star$	$\frac{A_2}{A_1}$	$J_{high/low}$	Location	Estimated location
$2.04 \cdot 10^{-7}$	-	-	-	-	High	-

5.3.5 Unknown leakage, surrounding temperature

The estimated leakage area when using the surrounding temperature is shown in Figure 5.19. Also for this leakage there is a small overshoot in the beginning as for Leakage 2 and Leakage 3. The explanation is also the same and the temperatures are shown in Figure 5.20. The size of the overshoot is however small since the leakage is large, making the influence of temperature change smaller.

The isolation results for isolation between high or low pressure circuit are shown in Table 5.16 and the isolation results from after that the circuits have divided is given in Table 5.17.

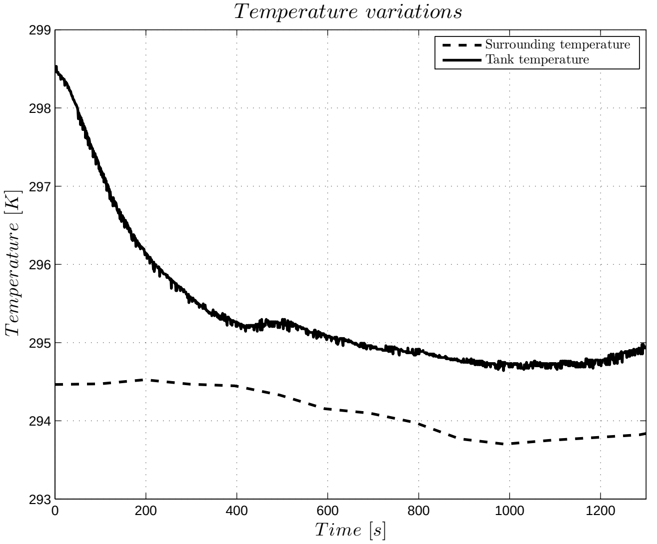

Figure 5.20. Temperature measured in the tanks compared to the surrounding temperature, for Unknown leakage. There is a difference in the beginning between the surrounding temperature and the air temperature in the tanks. The temperatures are almost equal after 400 seconds.

Table 5.17. Results from isolation algorithm using the surrounding temperature, Unknown leakage. The results shows that the leakage is in the rear brake circuit.

A_{front}	A_{rear}	A_{park}	$A_{auxilliary\ and\ suspension}$
$-1.93 \cdot 10^{-10}$	$2.07 \cdot 10^{-7}$	$-2.26 \cdot 10^{-10}$	$-2.31 \cdot 10^{-9}$

Chapter 6

Conclusions

A diagnosis algorithm for detecting and isolating leakages in the compressed air system has been developed. The diagnosis system is model based and uses a least mean square, LMS, method to estimate the leakage area. The development of the diagnosis system has been done by using data collected from real trucks. It is shown that it is possible to detect leakages that are as small as 1 litre/minute and that the exact circuit for where the leakage is present can be pointed out. The final test of the algorithm is done with measurement data that not has been used during the developing process.

6.1 Results from validation

The validation results show that the diagnosis algorithm works well for the tested leakages. For all implemented leakages the leakage is detected and isolated to the correct circuit. The estimated area is close to the expected value and has no oscillations and no under or over shoots neither which is good. The limitations of the algorithm can be seen for the unknown leakage area where the isolation between the high and low pressure circuits is missed. For larger leakages the algorithm loses full isolation performance, therefore the two circuits without pressure sensors cannot be isolated from each other for this types of leakages. The filter parameter was also a little too small for the second estimation which can be seen by studying the pressure simulations in Figure 5.5 and Figure 5.8.

6.1.1 The use of surrounding temperature

When the surrounding temperature is used instead of the measured temperature in the tanks the estimations becomes a little inaccurate. The inaccuracy depends on that the temperature in the tanks sometimes is a little higher than the surrounding temperature when the vehicle is turned off. The largest percentage difference is 11% given for A_1 Leakage 3. The largest difference between the surrounding temperature and the temperature in the tanks seems to be directly after that the vehicle has been turned off. A way to use the surrounding temperature is to wait a short while before making the first estimation. This might however affect the possibility to do the isolation between the high and low pressure circuits.

6.2 Final conclusions

The final conclusions in this thesis is that parameter estimation of the leakage area, using LMS together with a model for the system and a leakage, can be used for detecting leakages in the compressed air system for a heavy truck. It is possible to get full isolation performances although the pressure in the system must for example be high enough in order to get information about if the leakage is in a high or low pressure circuit.

The change in leakage area, discussed in Section 4.5, is one example of uncertainty that affects the results. However, the validation results show that the diagnosis algorithm is performing well for leakages around 1-10 litres/minute. In order to get the algorithm working fully for larger leakages some improvements are necessary.

6.3 Future work

To improve the diagnosis algorithm some points that can be further analysed are:

- **Model improvement**

  In order to get better estimations there is needed to get a better model. The temperature compensation that is discussed in this thesis is making the estimations of the leakage area more accurate. A model that is better when using the surrounding temperature could however be an interesting future development of the diagnosis system.

  There are also a trend that can be seen in some of the estimations where the estimated area is decreasing when the pressure in the system decreases. The study for one vehicle is presented in Section 4.5 but further analysis of more vehicles with different types and sizes of natural leakages could be interesting to analyse in order to improve the model.

- **Confidence interval**

  Another interesting thing that can be improved is the evaluation of the performance that is achieved. A confidence interval for the area estimations should be interesting to study and to see how it decreases or increases if more or less measurement data is used.

- **Smoothing**

  The estimations could also be improved by for example using smoothing on the estimations given by the LMS.

- **Adaptive μ**

For larger leakages the pressure decreases faster and in order to get full isolation performance, the parameter μ cannot be too small. For smaller leakages the value of μ is desired to be smaller since it gives a better accuracy of the estimations. An algorithm that adapts μ in a smart way depending on the leakage size might improve the results.

- **Driving vehicle**

  Because the model seems to work at least quite well it would be interesting trying to use the model on a vehicle that is driving. The model then have to be extended with the air consumers such as the brakes, suspension and the air used by the engines auxiliary components. The advantage is that the diagnosis could be performed on vehicles that are never turned off. To simplify the extension of the model the diagnosis could for example be performed at a stop for a red light. The engine can then be assumed to be idle and therefore maybe using a constant amount of air over time and there should be no braking that uses a lot of air. The challenge in this approach is, in addition to extend the model, that the interval of time is limited and since the circuits will not be isolated at any time, fault isolation will be difficult. The best fault isolation performance that can be accomplished, using the isolation strategies used in this thesis, will be limited to only tell if the leakage is in a high or low pressure circuit.

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Appendix A

Pressure drops

Pressure drops corresponding to the data used in Table 4.2 and Table 4.3 and also the pressure drops for the data used in the validation.

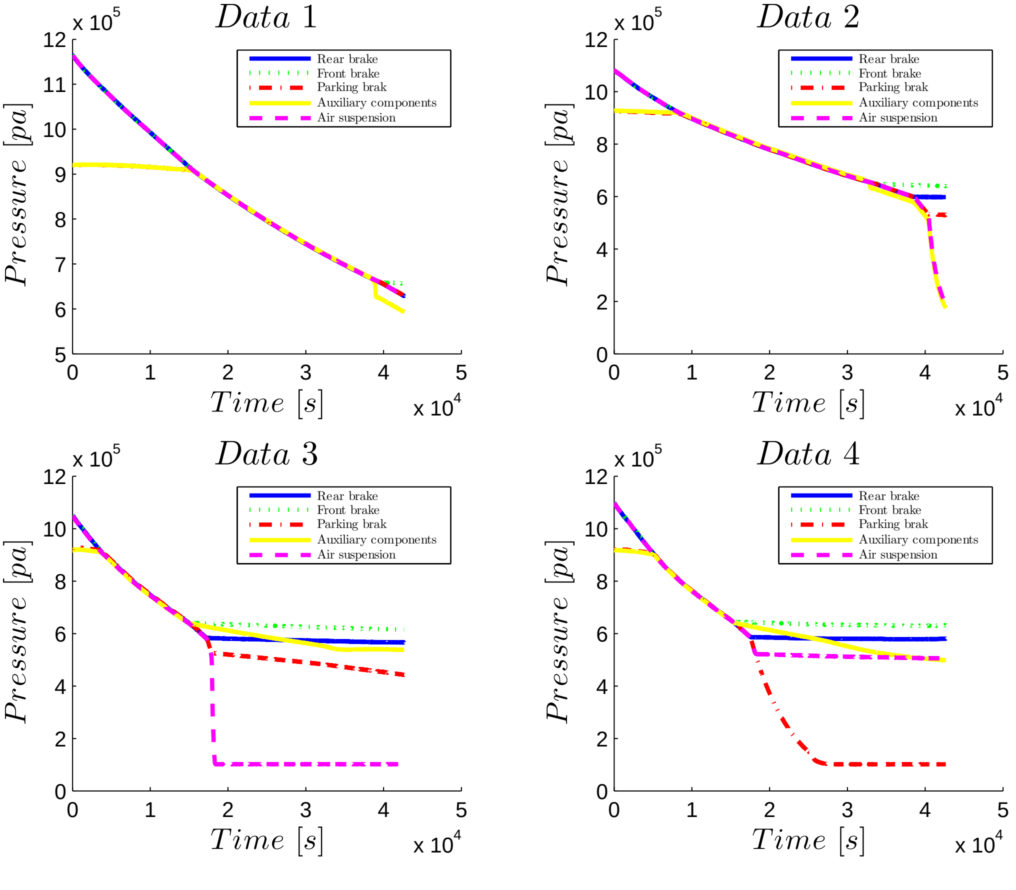

Figure A.1. Pressure drops corresponding to Data 1-4 used in Table 4.2 and Table 4.3.

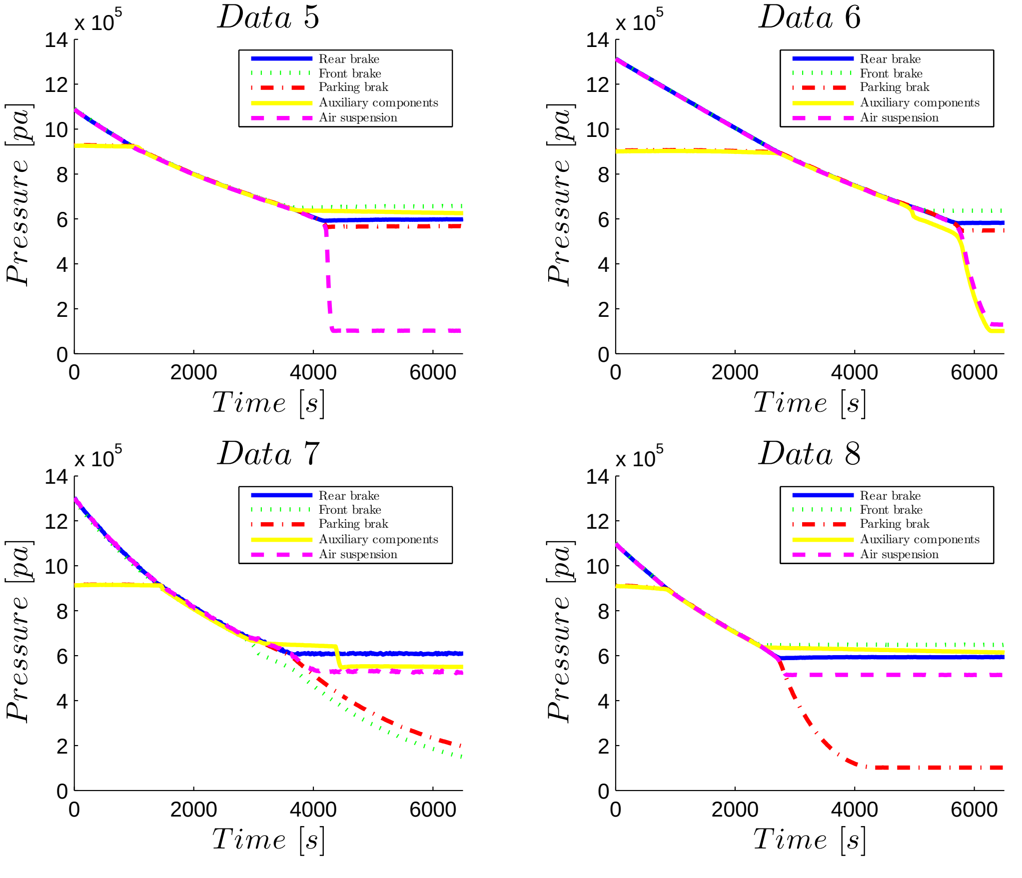

Figure A.2. Pressure drops corresponding to Data 5-8 used in Table 4.2 and Table 4.3.

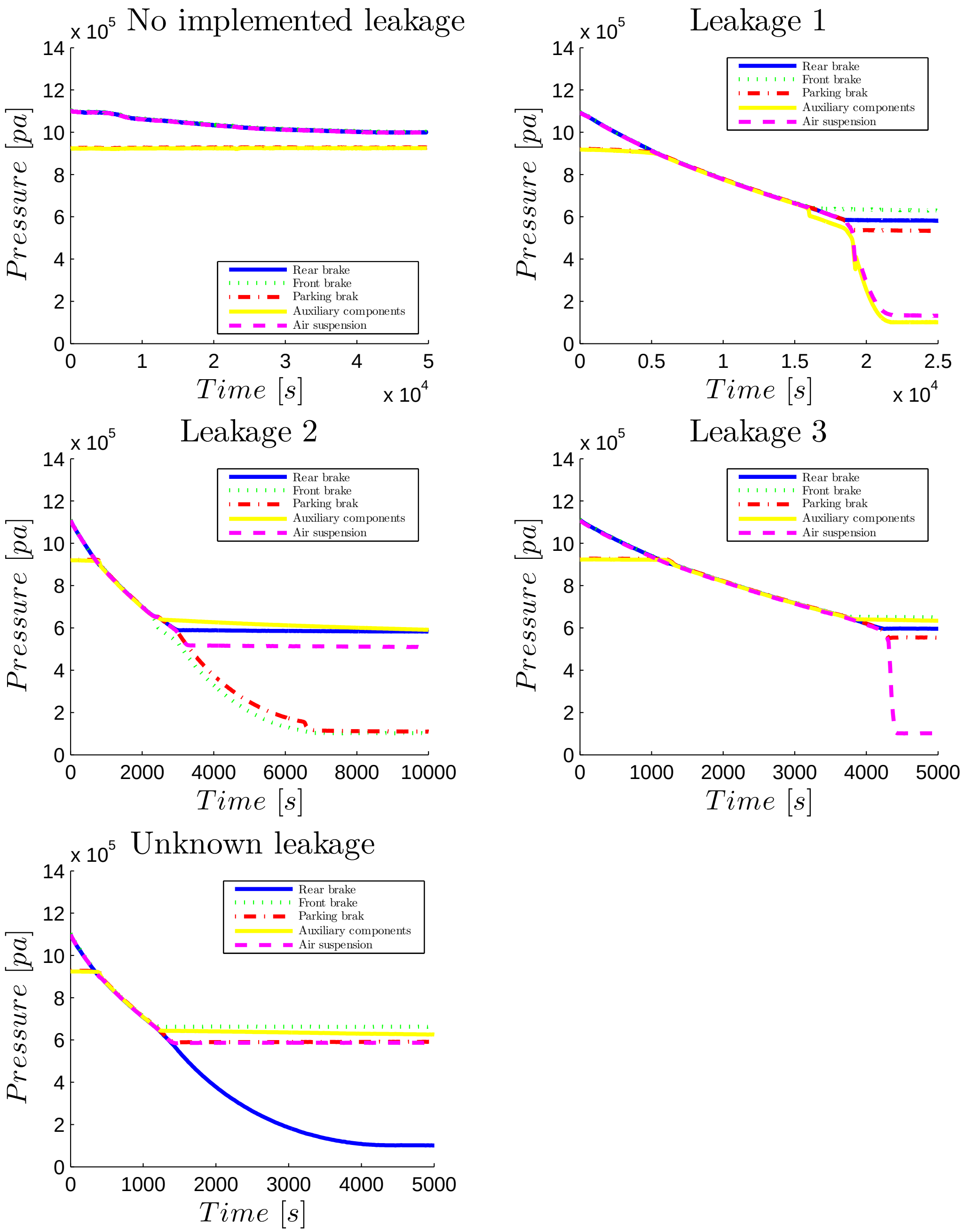

Figure A.3. Pressure drops for data used in the valiation.