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Recursive Identification of Respiratory Parameters

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Abstract

This master thesis describes a collaboration between ASTRA DRACO AB and the Department of Automatic Control in LUND. The goal has been to see whether it is possible to convert a least-squares estimation method used today into a recursive least-squares estimator with capability to follow time-varying parameters. This was found possible.

The parameters that are of interest are breathing parameters, ASTRA DRACO AB would like to be able to follow changes in the bronchitis and lung continuously, today it is only possible to make parameter estimations on one breath at the time. The idea is to see if a recursive estimator can work although there are large disturbances acting on the system. The "system" is a sheep that is used in an experiment which investigates if asthma medicine has any affect on an asthmatic sheep.

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PREFACE

Even though this thesis is a one man project many persons have helped me in many different ways. I would therefore like to take the opportunity to acknowledge their contributions. First of all I would like to thank my supervisors Bo Bernhardsson and Rolf Johansson for many good advices, excellent supervision and proof-reading. At ASTRA DRACO AB I would like to thank the electronic department and especially Johan Waldeck and Per-Olof Fagerström for their help. They were also the ones who proposed the thesis. At the Pharmacology 1 I specially would like to thank Lennart Lundblad for all help and that I could come and make my measurements on "his" sheep, hopefully without causing to much trouble. The excellent software on the Department of Automatic Control has been of invaluable help. I would like to thank Leif Andersson for helping me whenever there was some problem with the computers and Rolf Braun for the help when I borrowed equipment from the Department of Automatic Control. I also would like to thank all the people at both departments who has helped me in any way.

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LUND, JUNE 1992
JAN JOHANSSON

SUMMARY

This master thesis describes a collaboration between ASTRA DRACO AB and the Department of Automatic Control in LUND. The goal has been to see whether it is possible to convert a least-squares estimation method used today into a recursive least-squares estimator with capability to follow time-varying parameters. This was found possible.

The parameters that are of interest are breathing parameters, ASTRA DRACO AB would like to be able to follow changes in the bronchi and lung continuously, today it is only possible to make parameter estimations on one breath at the time. The idea is to see if a recursive estimator can work although there are large disturbances acting on the system. The "system" is a sheep that is used in an experiment which investigates if asthma medicine has any affect on an asthmatic sheep.

The thesis is organized in the following way. Chapter 1 gives background to the thesis and what asthma is. Chapter 2 deals with a mathematical model of the air-system, the dynamic lung model, and some problems involved when sheep is used as experimental animal. The different parameter estimation methods are described in Chapter 3 and a short descriptions of the measured signals are given. Chapter 4 shows the parameter estimations with two different methods and shows that the recursive estimator can cope with rather large disturbances. The results of the thesis are summarized in Chapter 5. Chapter 6 discusses implementation issues.

In appendix A the MATLAB-code and SIMNON-code for the parameter estimation is reproduced, appendix B shows the measurement set-up.

Based on the recursive estimator in Eq. 3.9 there will be made an implementation, in Modula-2 code, in Dracos measurement system and after a validation of the method in practise it might be used instead of the existing estimation method.

1. Introduction

This chapter gives some background to the thesis and a short description of asthma.

1.1 Background

ASTRA DRACO AB (Draco) is a company, located in Lund Sweden, which is doing research in respiratory medicine. The company is developing and improving drugs which prevent or reduce attacks of asthma. There are two types of drugs, which are either mitigating the underlying inflammation or widening the airways. To be able to see what effect the medicine gives and to find new improved medicines, there must be done some animal experiments. One such experiment which is done at Draco, is to see what effect the medicine has on a rather large animal. The animal is exposed to an allergy developing substance, allergen, and after a while treated with some curing substance. At Draco these experiments are performed on sheep, about 20 sheep has been selected. This means that a sheep is used for experiments approximately every third week. The sheep has been starving for 24 hours before an experiment is performed. The reason is that the stomachs should be as empty as possible to reduce the creation of gas. The sheep are very carefully examined and documented and the state of health of the sheep is followed all the time.

The idea to use sheep is quite unique and it is performed only at a couple of places around the world. The idea with the experiment is to see if there are any changes in the airways regarding contraction and widening or some elasticity changes in the lung. These changes can be tracked via two lungfunction parameters, compliance C and conductance G. The compliance is a measure of elasticity in the lung and the conductance is a measure of resistance in the air-passage

Draco has developed a technique to measure these changes in the airways. This technique is based on the "dynamic lung model", described in section 2.1. The pressure and airflow are measured and based on these measurements an estimation of the breathing parameters is done. Today the estimates of the parameters are based on one breath at the time. This thesis deals with an approach which considers all breaths that has been taken, using so called recursive identification. With this approach it is possible to show, "on line", changes in parameters that occur during the experiment.

A typical experiment consists of, in average, 5-10 measurement sequences at 1-5 minutes each. It has previously been considered that the breathing parameters are constant during a measurement sequence. The major advantages with the recursive identification is that it is possible to study the changes in the breathing parameters that occur during a measurement sequence and that such identification gives improved accuracy.

1.2 What is asthma?

During the last decades, asthma and asthma related diseases has increased considerably, especially among children and elderly people. It is believed that this is due to deteriorated indoor and outdoor environment. In Sweden it is estimated that 350 000 persons, 4% of the population, suffers from asthma. The number of people who dies in asthma every year, ≈ 600, equals the number killed in traffic.

Asthma is a disease that can strike all people in all ages. Asthma are in most cases developed early in life. About half of all asthma cases will strike before the age of nine. A person who, today, is stricken by asthma runs the risk of being isolated because it may be difficult to be in other peoples homes and public areas.

If you want to get a feeling of what it is like to have an asthma attack, it is said that a fairly slight attack is like breathing through three straws, a medium attack is like breathing through two straws and a severe attack is like breathing through just one straw.

Basically asthma means that the bronchi are contracting with following breathing difficulties. The disease also means a chronic inflammation in the bronchi. Many different things can bring about an asthma attack, both outer substances like perfume, tobacco smoke and pollen or other influences like infections, strain and cold air. Asthma is diveded into two different groups, atopic asthma and non allergical asthma.

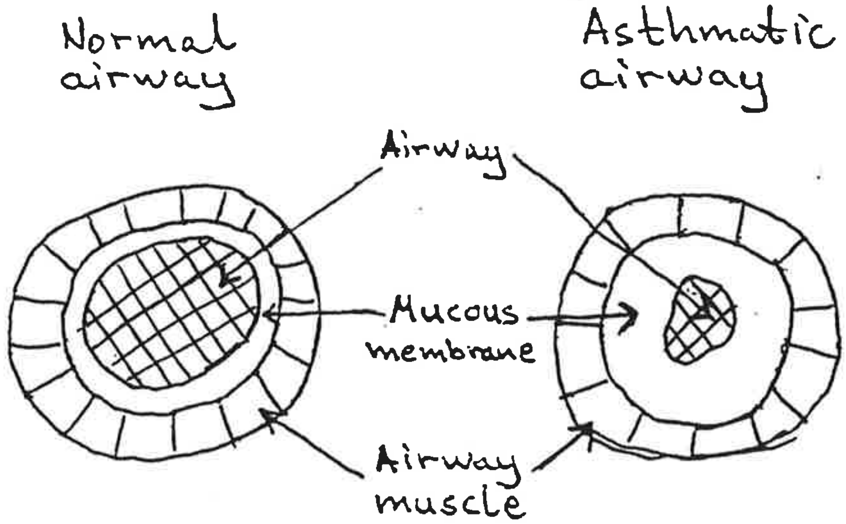

Figure 1.1 A schematic figure showing how the airway will contract when a person is having an asthma attack

Atopic asthma means that one has a hereditary inclination to react allergically. If one of the parents has got atopic asthma there is a probability of 20% that the children will get it to. An environment which is allergy rich, like having pets such as cats and dogs, dramatically increases the risk of developing asthma. By repeated contacts with allergens the immune defense reacts and produces large amounts of antibodies*, so called IgE**-antibodies. These antibodies will attach themselves on mast-cells† which are present in the mucous membrane in the bronchi. Due to this overproduction of IgE the person has become overreactive, sensibilisized, to certain allergens. Once overreactive only a small amount of the allergen is needed to create an allergic reaction. When the allergen comes in to contact with the IgE-antibodies a reaction is triggered in the mast-cells which releases histamine‡ and other chemical substances. Histamine and the other substances affect the blood vessels, musculature and glandular. This reaction entails a cramp in the musculature and enhanced mucous production from the mucous membranes in the bronchi. This leads to a contraction of the bronchi.

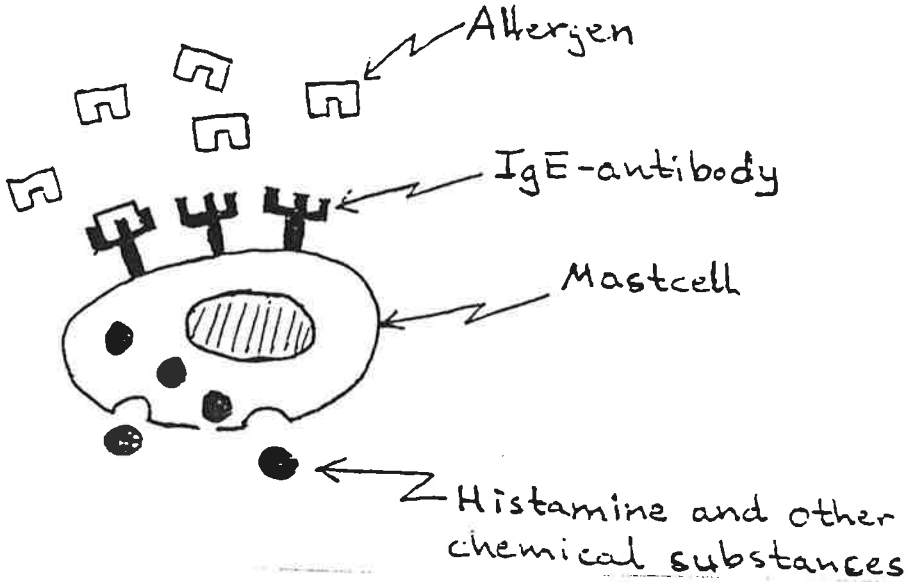

Figure 1.2 A schematic figure showing how the mastcell is realising histamine and other chemical substances when an allergen comes in contact with IgE-antibodies that are attached to the mastcells

The *non allergical asthma* is not as well understood as the atopic asthma. It is known that persons with non allergical asthma do not have increased values of IgE-antibodies but instead have very sensitive airways. According to some theories the causes can be, increased sensitivity in the mucous membrane nerve tips, abnormal subversion of signal substances or changed metabolism in the bronchi muscles cells. Asthma like this can be triggered by strain, tobacco smoke or some other irritating particles.

The allergical asthma is more common among younger people and the non allergical among elderly people, but still the underlying cause is a chronic inflammation in the bronchi.

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* Antibodies: A defense substance in the body that can work in three ways. 1) It can cover the alien particle and then be transported out of the body. 2) It can join up with the invading particle and then disturb the invader so no harm will be done to the body. 3) It can with help from other blood-components destroy unknown substances in the body.

** IgE: An antibody which plays a major role in the body defense against parasites and it is involved in an allergical reaction.

† Mast-cells: A cell which in an allergical reaction will set free histamine and other chemical substances.

‡ Histamine: A substance which enhance the defense against inflammations

Diagnosis and treatment

Determination of asthma demands a detailed examination of a persons way of life and surrounding environment. This is usually enough to determine the cause of asthma. To get better knowledge of what kind of allergic asthma a person has got it is possible to make three different tests. A skin test means that an allergen is placed under the skin and after 15-20 minutes it can be seen if there has been an allergic reaction. In a RAST-test a blood sample is tested against different allergens and in a PRIST-test the content of IgE-antibodies is measured to determine whether it is an atopic or a non allergic asthma. There are also made tests on the lungfunction to see if the person has got asthma or not.

If the allergen has still not been determined there can be made some provocation tests. With provocation tests is meant that different allergens are inhaled. The test is very time consuming because it is important to start with small doses and slowly increase the amount.

Asthma medicines can be taken in different forms such as inhalation, tablets, injection or in a liquid form. Usually a combination of airway widening and inflammation mitigating medicines is used.

2. A mathematical model

This chapter presents a mathematical model of the lung. The experimental conditions are also described.

2.1 Dynamic lung model

If the breathing system is seen from a pure mechanically view, the lung can be considered to be like a balloon. This balloon can have difficulties to let the air through the balloon tip, which equals the bronchi, and the elasticity of the balloon may vary, which is comparable to the elasticity of the lung. The lung model is shown in Fig. 2.1. One model that is considered to model the mechanical function of the lung quite well is:

$$P = \frac{1}{C}V + \frac{1}{G}\dot{V} + T\dot{V}^2 \tag{2.1}$$

P = Difference between outer and inner lung pressure	(kPa)
C = Compliance	(ml/kPa)
G = Conductance	$(ml/(kPa * s))$
V = Exchanged volume	(ml)
$\dot{V}$ = Airflow	(ml/s)
T = Turbulence coefficient	$(kPa * s^2/ml^2)$

A negative pressure and airflow is chosen for expiration and vice versa for inhalation. Based on this simple model it is possible to determine the parameters C, G and T. The parameter C is a measure of the reciprocal elasticity of the lung. As mentioned before the parameter G is a measure of the reciprocal resistance of the airway. The parameter T describes turbulence in the airway. The airway can be viewed as a cylindrical pipe and it has been shown for cylindrical pipe like the airway, see Wald and others (1969), that there will only be laminar airflow in the pipe and therefore the parameter T will be zero. In this model, dynamics of higher order has been neglected.

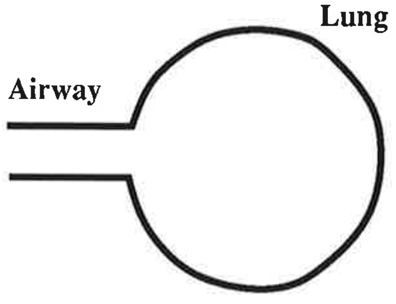

Figure 2.1 The model of the breathing-system which is used in the dynamic lung model.

There is always a certain pressure in the pleura, which may vary. This can be represented by a bias term, that may vary with time.

$$P(t) = \frac{1}{C}V(t) + \frac{1}{G}\dot{V}(t) + P_0(t) \tag{2.2}$$

Model 2.2 is sufficiently good for our intentions and is also used elsewhere.

measurements

When performing the experiment it is possible to measure pressure, P, and airflow, $\dot{V}$. The volume is very difficult to measure but by taking the time integral of the airflow, the exchanged volume can be calculated. When the volume is calculated there might have been a bias term in the airflow, which will lead to a ramp in the volume when taking the time integral of the airflow.

$$\int(\dot{V} + \gamma)dt$$

where γ is a bias term in the airflow measurement. This must be taken into account so therefore Eq.2.2 becomes

$$P(t) = \frac{1}{C}V(t) + \frac{1}{G}\dot{V}(t) + P_0(t) + \gamma t \tag{2.3}$$

Based on measurements of P and $\dot{V}$ it is possible to make estimation on C and G, see chapter 3.

During an asthma attack the values of C and G are changed, both values becomes smaller.

2.2 Sheep as laboratory animal

Like other cloven-footed animals the sheep is a ruminant. This means that the sheep ferments the food in the stomachs. This fermentation will create a lot of gas which will make the sheep belch. This belching will disturb the measured signals. Another disturbance is when the sheep swallows and moves around. The most prominent disturbance is the belching. When these disturbances are present Eq. 2.3 is not valid, therefore the disturbances must be taken away. In Fig. 2.2 a short breathing sequence for the measured pressure is shown, where every peak equals one breath. It is very prominent in the pressure curve when a disturbance is present, this is marked with an X in the figure. These disturbed breaths has earlier been taken away when estimating C and G. With the new approach it is possible to take away disturbed breaths automatically and still make trustworthy estimations. This makes it easier to directly understand the effect of different medicines and in detail study the picture of the disease.

It is difficult to measure pressure in the pleural cavity, because the pleura is "sealed" of. It is possible to measure pressure in the pleura indirectly by placing a balloon in the middle of the esophageal. This balloon is connected to an indicator which indicates the pressure changes in the balloon. This is considered to equal the pressure changes in the pleura. This is probably a good approximation. The airflow is measured with an ordinary airflow meter, which is connected to the sheep via a tube which goes through the nostril and

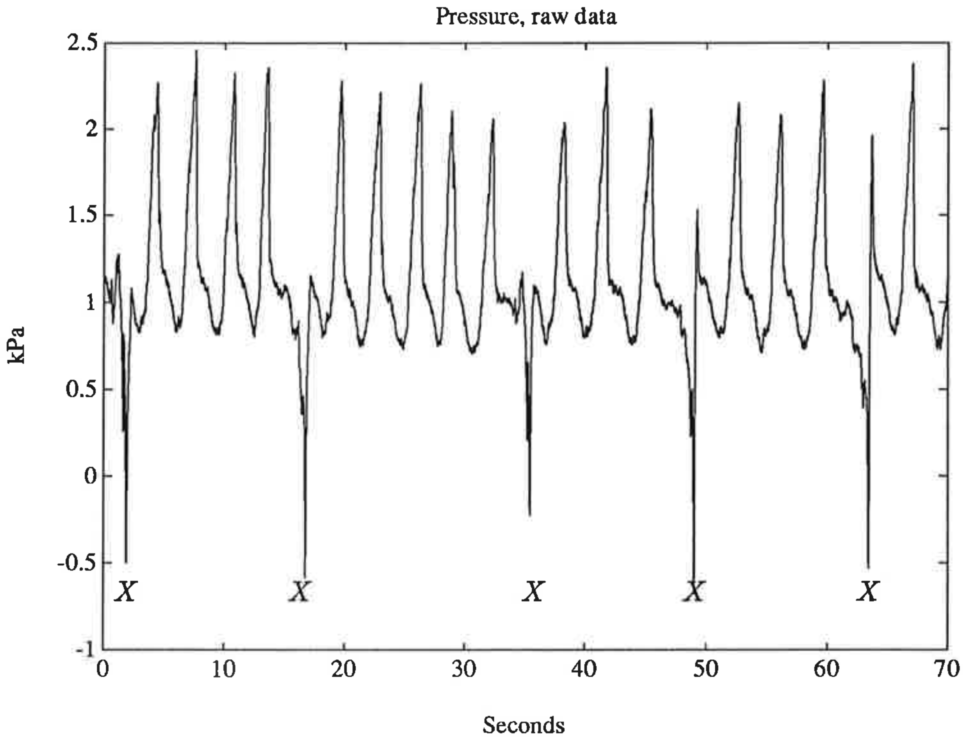

Figure 2.2 A short sequence, 70 seconds, showing the variation in measured pressure, P, when the sheep is breathing. Outer disturbances, like belching and swallowing, are marked with an X.

the nasal cavity down to the beginning of the bronchi. The measured signals, airflow and pressure, is transmitted to amplifierers and a low-pass filter with a cut-off frequency of 50 Hz. The experimental arrangement can be seen in Appendix B. An oscilloscope is also used to see if the signals are good. One thing that can go wrong is that the pressure balloon can be placed to close to the heart, which will disturb the pressure signal. During an experiment the sheep is not allowed to eat or drink.

A healthy sheep is breathing with a rate of 10-20 breaths per minute but it is possible that they sometimes breath with a rate of 60-80 breaths per minute. To be sure that no information is lost the measured signals are sampled with 100 Hz (Nyquist frequency = 50 Hz)

The measurements treated in this thesis has been performed at Draco during December 1991 to February 1992. They were performed at three different occasions. The first measurement series was not good due to quantization effects from the A/D-converter. This problem was overcome by simply amplifying the measured signals before sampling them. At the two other occasions, one was a routine measurement and the other a so called trend measurement. The collected data have been analyzed by using the software program MATLAB, which is a widely spread program that is used on many engineering schools all over the world. MATLAB also has routines for parameter estimations.

Before bringing the sheep to an asthmatic state, pressure, airflow and volume is measured and an estimation of C and G is done.

By a routine measurement is in this case meant that the sheep is exposed to a known dose of Ascaris. The reason for this experiment is to see if the sheep is allergic. If the sheep is allergic it can be used in later tests. About

50% of the sheep shows asthmatic reactions, which will make the parameters C and G change. The experiment runs for approximately eight hours and the values of C and G is saved during the day. With the occurring method the changes of C and G will be analyzed at the end of the day and it is first after that possible to say if there has been an asthmatic reaction or not.

In the trend measurement the sheep was exposed to Methacoline, which will give a bronchi contraction. The reson for this measurement was to see if the recursive approach treated in this thesis was capable of following parameter changes.

3. Parameter estimation methods

This chapter deals with different estimation methods that have been found to work very well. The data collection and limitations in the analysis will also be described. Different validation methods are also shown.

3.1 Estimation-theory

Least-squares method

The aim of the experiments are to estimate the parameters C and G, based on Eq. 2.3, given noise-corrupted measurements of the pressure and airflow. One way to estimate C and G is to use least squares estimation. This method was first described by the mathematician K.F Gauss* in the 19th century and is a standard choice in identification

Eq. 2.3 is an ARX-model, autoregressive model with exogenous input, which can be written in a linear regression form as:

$$Y_N = \Phi_N \theta \tag{3.1}$$

where

$$Y_N^T = \begin{pmatrix} y_1 & y_2 & \dots & y_N \end{pmatrix}$$

$$\Phi_N = \begin{pmatrix} \phi_1^T \\ \phi_2^T \\ \vdots \\ \phi_N^T \end{pmatrix} = \begin{pmatrix} V_1 & \dot{V}_1 & 1 & 1 \\ V_2 & \dot{V}_2 & 1 & 2 \\ \vdots & \vdots & \vdots & \vdots \\ V_N & \dot{V}_N & 1 & N \end{pmatrix}$$

$$\theta^T = \begin{pmatrix} \frac{1}{C} & \frac{1}{G} & P_0 & \gamma \end{pmatrix}$$

Here $y_1 \dots y_N$ are all the model output pressures and $\phi_1 \dots \phi_N$ contains the time varying regressors for each measurement sample. θ contains the parameters that will be estimated

The goal for the least squares estimation is to find the estimated θ, $\hat{\theta}$, which minimizes the quadratic error between the assumed linear regression model output and the observed output, pressure, from the sheep.

$$\min_{\hat{\theta}} \sum_k (y_k - \phi_k^T \hat{\theta})^2 \tag{3.2}$$

where $\hat{\theta}$ is the estimate of θ and y_k is the observed pressure at time k.

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* He lived in the end of 18th century and beginning of the 19th century and used the method to predict orbits of planets

Minimum for Eq. 3.2 will be obtained for the optimal estimate.

$$\hat{\theta} = (\Phi_N^T \Phi_N)^{-1} \Phi_N^T Y_N \tag{3.3}$$

The least squares estimate has some attractive features like straight forward calculations, it punishes large errors, and the estimated parameters are under some conditions unbiased. A drawback of the least square method is that it is sensitive to colored noise.

Today Eq. 3.3 is used at Draco, except they do not take into account the ramp term, t, to estimate C,G and P_0 during the experiment.

Another way to approach Eq. 2.3, which is used in this thesis, is to make a band-pass filtering of the signals, where the lower cut-off frequency takes away bias in the signals. By doing this the bias terms, P_0 and γ, in Eq. 2.3 will disappear and we obtain.

$$Y_f = \frac{1}{C} V_f + \frac{1}{G} \dot{V}_f \tag{3.4}$$

where

$$V_f = \frac{F(s)}{s} \dot{V}$$

$$\dot{V}_f = F(s) \dot{V}$$

where $F(s)$ is a suitable band-pass filter.

Eq. 3.4 can be written on linear regression form. With the prefiltering approach we do not have to estimate P_0 and γ.

$$Y_{Nf} = \Phi_{Nf} \theta \tag{3.5}$$

where

$$Y_{Nf}^T = (\, y_{1f} \quad y_{2f} \quad \dots \quad y_{Nf} \,)$$

$$\Phi_{Nf} = \begin{pmatrix} V_{1f} & \dot{V}_{1f} \\ V_{2f} & \dot{V}_{2f} \\ \vdots & \vdots \\ V_{Nf} & \dot{V}_{Nf} \end{pmatrix}$$

$$\theta = (\, \tfrac{1}{C} \quad \tfrac{1}{G} \,)^T$$

By band-pass filtering, the estimation of the parameters has been reduced to only two parameters instead of four parameters. It can be suspected that the estimates will be more accurate. The conclusion of Eq. 3.5 will be that all signals should be prefiltered before used in the estimation algorithms. We want the filter, $F(s)$, to pick out the frequency region where the signals "are most interesting" and has "best signal/noise ratio". The choice of band pass filter is discussed in sec 3.2.

For a detailed derivation of the least squares estimation look in Johansson. R (1991).

Recursive least-squares method

In this thesis the estimation is done with recursive identification and by using band-pass filtered signals. This means that earlier measured signals will be taken into account when estimating the new parameters.

The recursive least square estimation, for a derivation look in Åström and Wittenmark(1990), is given by:

$$\begin{aligned}\hat{\theta}_k &= \hat{\theta}_{k-1} + P_k \phi_k \epsilon_k \\ \epsilon_k &= y_k - \phi_k^T \hat{\theta}_{k-1} \\ P_k &= P_{k-1} - \frac{P_{k-1}\phi_k \phi_k^T P_{k-1}}{1 + \phi_k^T P_{k-1} \phi_k}\end{aligned} \tag{3.6}$$

where

$P_k = \left(\sum_{i=1}^{k} \phi_i \phi_i^T \right)^{-1}$ covariance matrix
$\phi_k^T = \begin{pmatrix} V_k & \dot{V}_k \end{pmatrix}$ regressors
$\epsilon_k =$ predicted error
$\hat{\theta}_k = \begin{pmatrix} \frac{1}{\hat{C}_k} & \frac{1}{\hat{G}_k} \end{pmatrix}^T$ estimated parameters
$y_k =$ measured pressure at time k

The recursive least squares estimation has a very nice appeal because it only adds on a correction factor to the last estimated parameter. Eq. 3.6 will take equal consideration to old measurements as to new measurements. The parameter estimates will then converge and stop to move

Forgetting factor
In the case with the sheep the idea was to be able to follow time-varying parameters. This means that old measurements should be "forgotten" and only relatively new measurements should be taken into account. There are different ways of doing this, one way is to introduce a so called forgetting factor, λ

$$J_\lambda = \sum_{i=1}^{k} \lambda^{k-i} (y_k - \phi_k^T \hat{\theta}_k)^2$$

this will change Eq. 3.6 to:

$$\begin{aligned}\hat{\theta}_k &= \hat{\theta}_{k-1} + P_k \phi_k \epsilon_k \\ \epsilon_k &= y_k - \phi_k^T \hat{\theta}_{k-1} \\ P_k &= \frac{1}{\lambda}(P_{k-1} - \frac{P_{k-1}\phi_k^T P_{k-1}}{\lambda + \phi_k^T P_{k-1} \phi_k})\end{aligned} \tag{3.7}$$

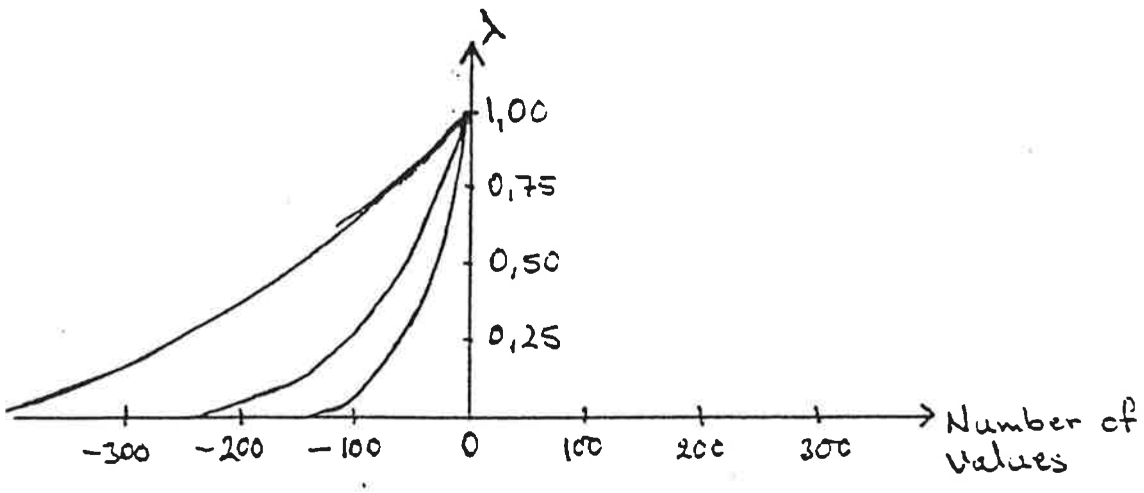


Figure 3.1 A schematic figure showing how many values back in time that will be remembered due to the forgetting factor λ.

The value of λ determines how fast data should be forgotten and should be between $0 < \lambda \leq 1$. A schematic figure of how the forgetting factor works can be seen in Fig.3.1. Usually one chooses a value on λ around 0.95-0.999. When deciding what value should be chosen, a trade-off should be made between how fast the following of the parameters should be and how noisy the estimation of the parameters should be. This is normally called the tracking/accuracy trade-off. When λ is decreased the faster Eq. 3.7 will be to follow parameters but it will be more sensitive to noise. A rough measure of how many measurement points that will be remembered is.

$$\text{Number of "remembered" data points} \approx \frac{2}{1-\lambda} \tag{3.8}$$

Algorithm Eq.3.7 is capable of following time varying parameters but it may be that the parameters are fluctuating with different speeds, see Fig. 3.2. If this is the case it would be nice to be able to have different forgetting rates connected to respectively parameters. This can be achieved with a so called Kalman-filter.

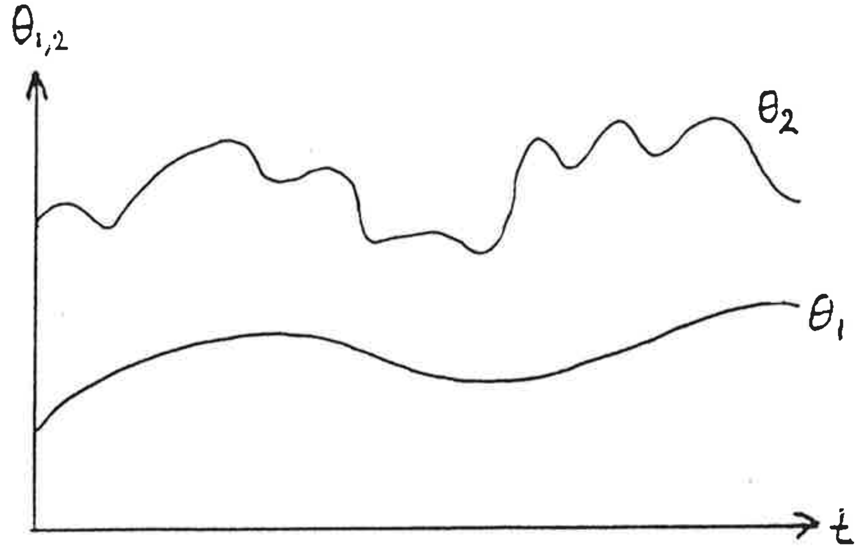


Figure 3.2 The parameters which will be estimated may vary with different speeds, like θ_1 and θ_2

Kalman-filter
An alternative to Eq. 3.8 is to assume that the time-varying parameters can be described by the state-space equation

$$\begin{aligned} \theta_k &= \theta_{k-1} + v_k \quad , E\{v_i\} = 0; \quad E\{v_i v_i^T\} = R_1; \\ y_k &= \phi_k^T \theta_k + e \quad ; E\{e_i\} = 0; \quad E\{e_i e_i^T\} = R_2; \end{aligned}$$

Here E denotes the expectation operator, v_k describes changes in parameters, R_1 the covariance of these parameter changes, R_2 the covariance of the measurement noise and $\{y_k\}$ is interpreted as a sequence of indirect observations of θ_k obtained from the observations y_k. The Kalman filter for estimation of θ_k from observation of y_k is.

$$\begin{aligned} \hat{\theta}_k &= \hat{\theta}_{k-1} + K_k \epsilon_k \\ K_k &= \frac{P_{k-1}\phi_k}{R_2 + \phi_k^T P_{k-1} \phi_k} \\ \epsilon_k &= y_k - \phi_k^T \hat{\theta}_{k-1} \\ P_k &= P_{k-1} - \frac{P_{k-1}\phi_k \phi_k^T P_{k-1}}{R_2 + \phi_k^T P_{k-1}\phi_k} + R_1 \end{aligned} \tag{3.9}$$

We have in Eq. 3.9 introduced two tuning terms, R_1 and R_2. With these terms it is possible to give the parameters different forgetting rates. The term R_1 is a matrix while R_2 is a scalar. By choosing R_1 and R_2 it is possible to let Eq. 3.9 follow the time-varying parameters C and G as fast as possible without being too sensitive to noise.

By rewriting 3.9 the tuning terms will be just one, R'_1.

$$\begin{aligned}
\hat{\theta}_k &= \hat{\theta}_{k-1} + K'_k \epsilon_k \\
K'_k &= \frac{P'_{k-1}\phi_k}{1+\phi_k^T P'_{k-1}\phi_k} \\
\epsilon_k &= y_k - \phi_k^T \hat{\theta}_{k-1} \\
P'_k &= P'_{k-1} - \frac{P'_{k-1}\phi_k\phi_k^T P'_{k-1}}{1+\phi_k^T P'_{k-1}\phi_k} + R'_1
\end{aligned} \tag{3.10}$$

where $P' = P/R_2$ and $R'_1 = R_1/R_2$. The forgetting rate therefore only depends on the ratio R_1/R_2. Normally R'_1 can be chosen as a diagonal matrix.

The parameters C and G in the ARX-model, Eq. 2.2, can now be estimated with recursive identification using a Kalman-filter which has the possibility to follow time-varying parameters. Now we have got the tools, to start estimating the parameters "on line" and compare them with Dracos estimated parameters. Special attention has to be taken to the intervals of bad data, belching. This is described in sec. 4.2.

Initializations

The starting values of Eq. 3.10 has been chosen by some preknowledge of typical values on C and G. Usually C is somewhere in between 200 - 1500 ml/kPa and G is somewhere in between 1000 - 2500 ml/(kPa*s). The starting value should be chosen somewhere in the middle of these parameter ranges. The parameters used in the recursive estimator are the inverted values of C and G. The P_0-matrix is a symmetric covariance-matrix. When we are sure of the starting value of C^{-1} and G^{-1}, P_0 is chosen like the squared values of C^{-1} and G^{-1}. If C^{-1} is chosen to be 1/700 and G^{-1} to be 1/1500 the P_0-matrix should have a value like $diag(8e-7, 8e-7)$. A larger P_0-matrix gives faster but also has more noisy transients. The R_1-matrix has been found to act good around a value of $diag(1e-9, 1e-11)$. This corresponds to a movement in the parameters of $sqrt(1e-11) = 3e-6$ per sample. A larger R_1 gives quicker tracking of time-varying parameters but lower accuracy. If the R_1-matrix is chosen to be zero and the P_0-matrix = c*I, where c is a large scalar and I is the unity-matrix, the Kalman-filter will equal a ordinary least-square estimator but the P-matrix must be reset to a large value every time there is a change in the parameters. The reason to this is that when making a recursive estimation the P-matrix will become smaller and smaller when the estimations becomes better and better and when a change in the parameters occur the P-matrix will be slow to make a new estimation.

3.2 Data collection

Measured data

The signals which are used are "raw" pressure and airflow signals. These signals are collected with a sampling rate of 100 Hz by an ordinary IBM-AT computer. The data collecting program have been developed at the department as a master thesis project, see Nilsson and Nilsson(1990). This program has the capability to collect data at a rate of 3-6 kHz but it is only possible to collect 32000 data points per measured signal. This gives in the case with a

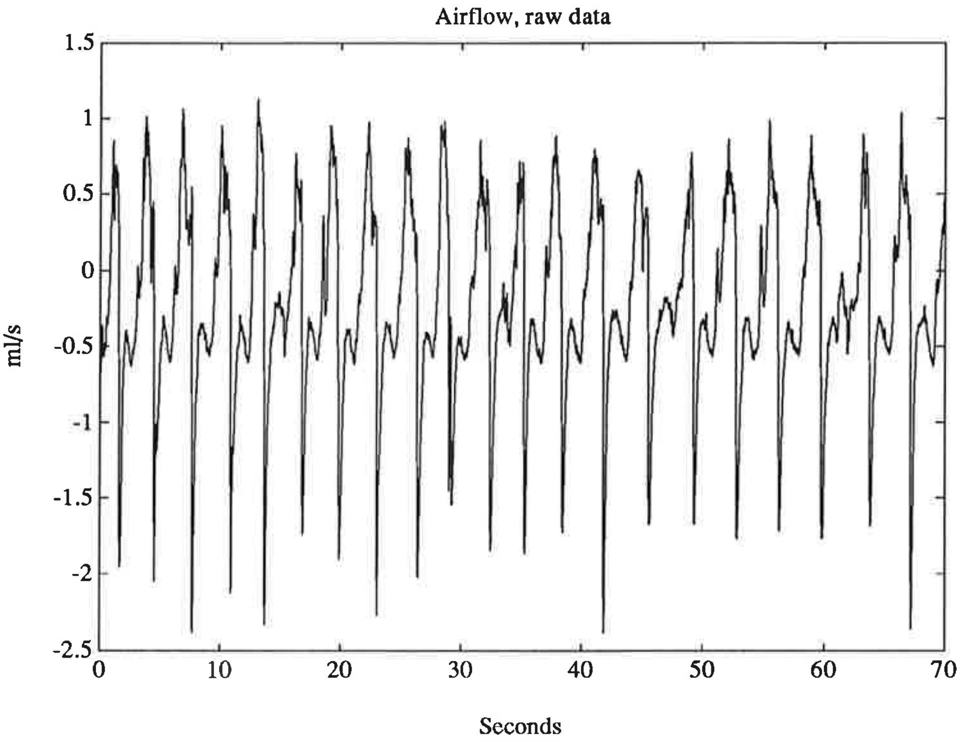


Figure 3.3 A short sequence showing the variation of the airflow when the sheep is breathing, 70 seconds and 21 breaths.

sampling rate of 100 Hz a possibility to store 320 seconds of "breathing-data" at the time

A typical part of a measurement sequence showing the pressure and airflow is shown in Fig. 2.2 and Fig. 3.3. These signals are raw data, which here means that they have been low-pass filtered at 50 Hz, internally in the measurement set-up. It can be seen that an outer disturbance, like a belch or swallowing, are very significant in the pressure plot, marked with an X. Looking at the airflow plot it is more difficult to see if there has been an outer disturbance.

As mentioned before we will make a band-pass filtering of the signals to get rid of the bias terms. The cut-off frequencies for the filter has been chosen according to what is said in the next section. The band-pass filtered signals is shown in Fig. 3.4 – 5.

This measurement sequence was collected on the 20th of January 1992 and it was made on a healthy sheep.

Control of collected data and validation

When both pressure and airflow signals has been collected there must be made some statistical control of the data so it can be assumed that an ARX-model, Eq. 3.1, will give the same pressure output as the real measured output.

Writing the filtered "dynamic lung model", Eq. 3.4, on transfer function form it becomes

$$Y(s) = \frac{1}{Cs}\dot{V} + \frac{1}{G}\dot{V} = \frac{1}{C}\frac{s + G/C}{s}\dot{V} = H(s)\dot{V} \tag{3.11}$$

where Y is the pressure, $\dot{V}$ is the airflow and H(s) is the transfer function.

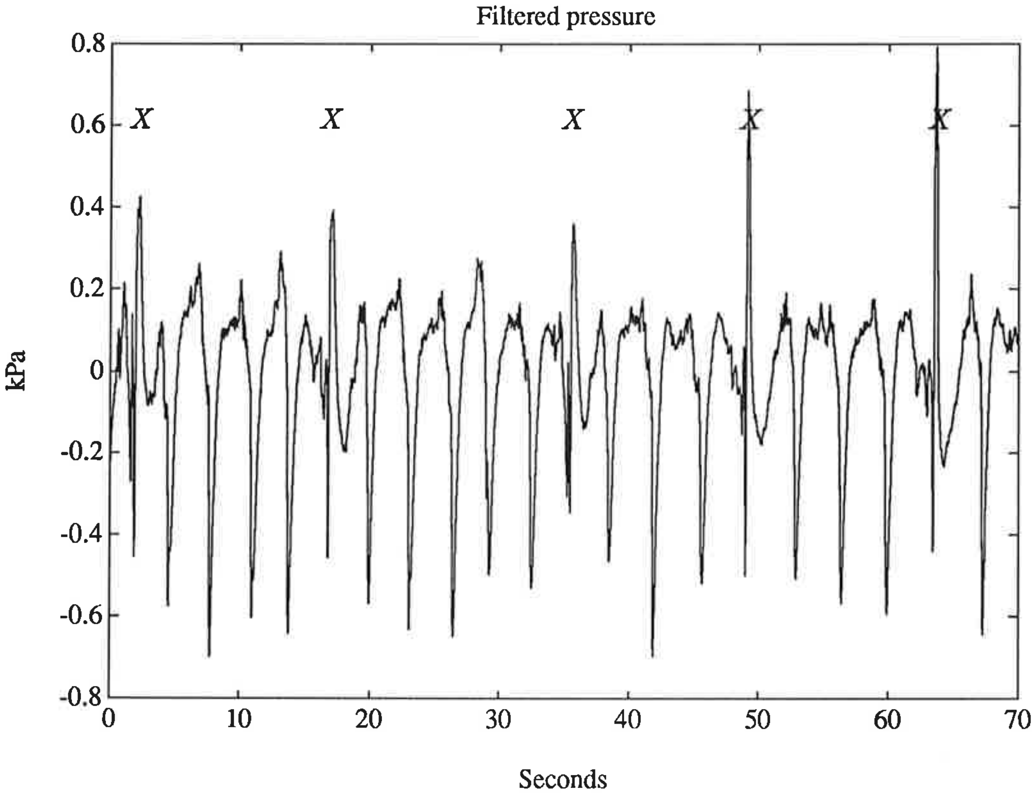


Figure 3.4 A short sequence showing the variation of the pressure when the sheep is breathing. This signal has been band-pass filtered and an outer disturbance is marked with an X.

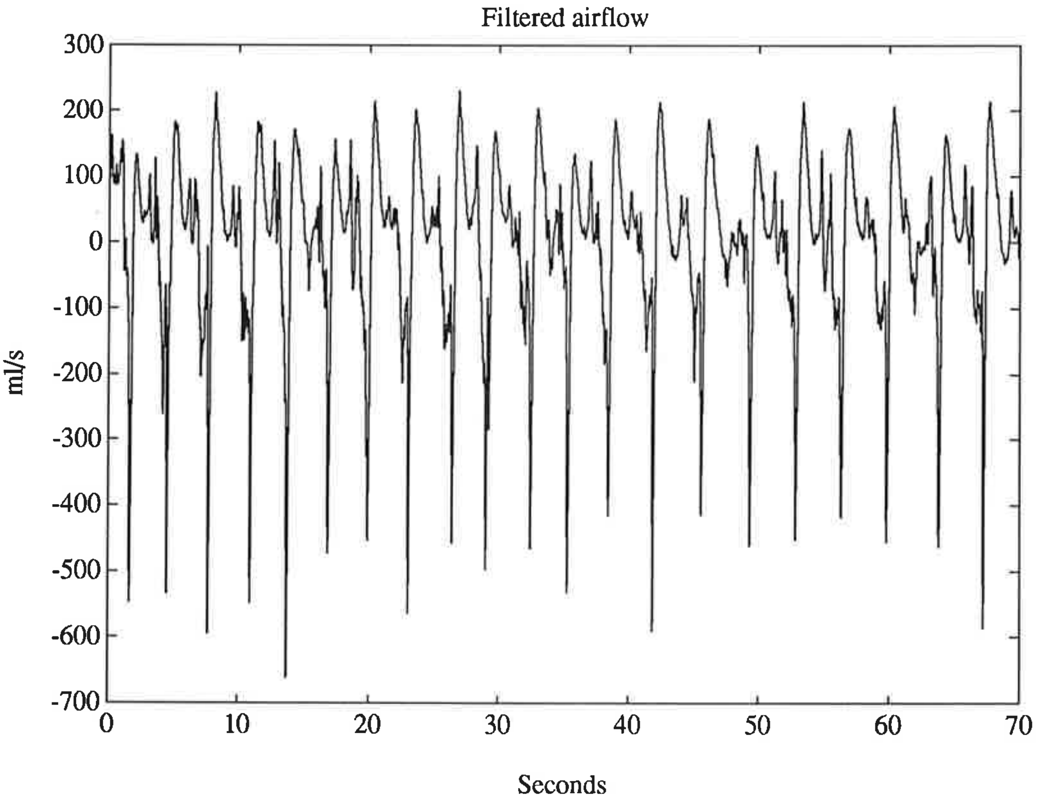


Figure 3.5 A short sequence showing the variation of the airflow when the sheep is breathing. This signal has been band-pass filtered.

From this it can be seen that the cut-off frequency will equal $G/2\pi C$. When approximating, $s = (z-1)/h$, this continuous model will in discrete time become

$$Y(z) = \frac{\frac{1}{G}z + \frac{1}{C}h - \frac{1}{G}}{z-1}\dot{V} = H(z)\dot{V}$$

where h is the sampling interval.

The Bode diagram for this parametric model can be seen in Fig. 3.6 with different values on C, G. Normally the value of C is smaller than the value of G and very seldom bigger than G. This will mean that the cut-off frequency off the model, usually, is $>$ 1Hz. Therefore the lower bandpass filter cut-off frequency can be chosen to be 0.1 Hz and the higher should be $<$ 30 Hz.

A way to check if the parametric model can be accepted is to make a Bode plot based on a non-parametric model. This can be obtained with frequency analysis. If both Bode plots looks the same, at least in a certain frequency range, it can be assumed that the model is valid in this frequency range. The frequency analysis uses the collected pressure and airflow signals to make a transfer function estimate, based on fast Fourier transform. The Bode diagram over the estimated transfer function can be seen in Fig. 3.7, this should be compared to curve a in Fig. 3.6 because C=279 ml/kPa and G=1700 ml/(kPa*s) in this case. The plots are based on filtered data. The transfer function is a bit noisy but it can be seen that between 0.3 Hz and 5 Hz, Fig.3.6 and 3.7 has the same behavior. The reason to the noisy transfer function might be that

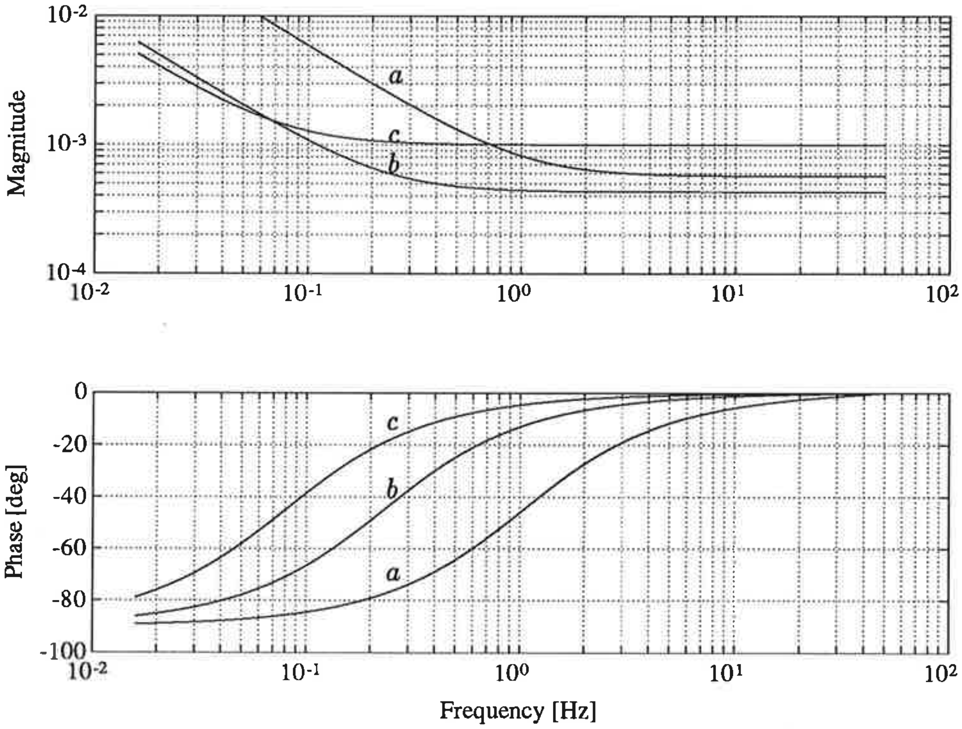
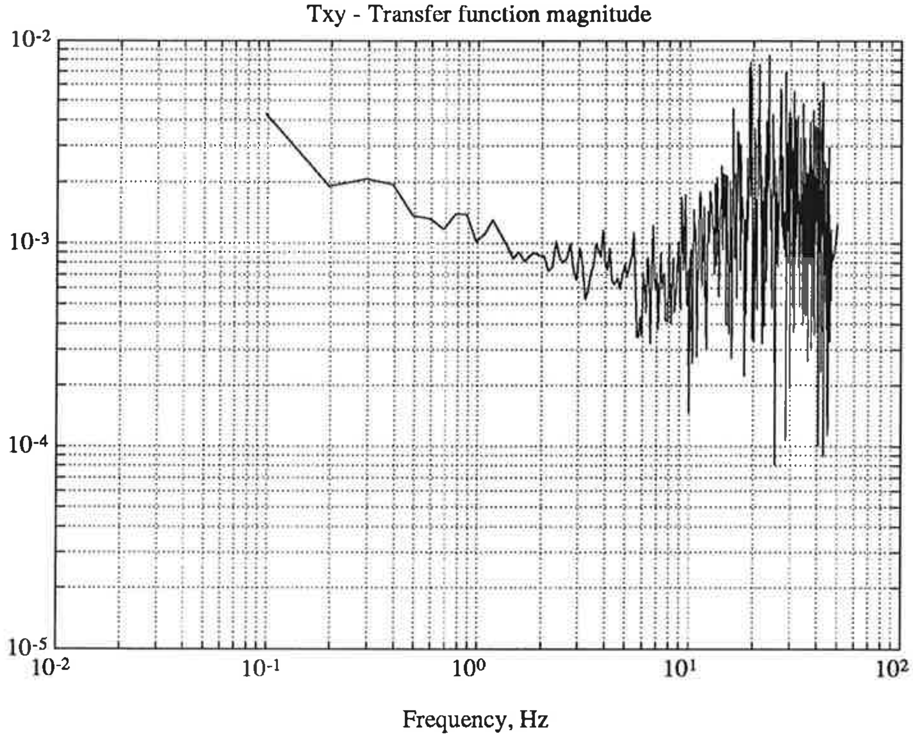


Figure 3.6 Bode-diagram for the transfer function $H(z) = \frac{\frac{1}{G}z+\frac{1}{C}h-\frac{1}{G}}{z-1}\dot{V}$. The transfer function has been drawn for different values on C and G namely a: $C = 279ml/kPa$, $G = 1700ml/(kPa * s)$, b: $C = 1600ml/kPa$, $G = 2300ml/(kPa * s)$ and c: $C = 2000ml/kPa$, $G = 1000ml/(kPa * s)$. The cut-off frequency is $G/C2\pi$ which corresponds to a: f= 1 Hz, b: f=0.23 Hz and c: f=0.08 Hz. The curve named a should be compared to the non parametric model in Fig. 3.7.

the frequency analysis is based on too few collected signals points. This is due to the outer disturbances, like belching, which makes it difficult to get long good sequences. Based on the same sequence as the frequency analysis was, it can be seen in Fig. 3.8 that the coherence between Y and $\dot{V}$ is good up to 5 Hz. The conclusion is that the model will give corresponding values to reality up to 5 Hz, except for very low frequencies.

There must also be made a validation of the model. This is done by making an estimation of the parameters C and G based on a measurement sequence and by using these estimations on another measurement sequence. It can then be seen if the estimated pressure sequence will correspond to the real. A validation done in this way can be seen in Fig. 3.9. There is quite good correspondence. In Fig. 3.10 the error between the predicted and the real output, pressure, can be seen in a histogram. The error is well gathered around zero and this is another indication that the model could be acceptable.

A correlation analysis was also performed based on the obtained estimations above and used in another measurement sequence. The interesting thing is to see what the correlation function of the residuals looks like and the cross correlation function between the residuals and volume and airflow. The correlation function are reproduced in Fig. 3.11. It can be seen that the cross correlation between the volume, residuals and airflow, residuals are good since they are inside the 3-standard deviation confidence limits, which means that there is no or very little correlation between the input and residuals. The correlation between the residuals is indicating that the residuals are not independent white noise. There can be several reasons for this. The calibration curves which should be straight, that is used to convert the measured signals so the estimations will be physical interpretable, shows a periodic disturbances. It can be seen in Fig. 3.12 that both in the unfiltered calibration curve and the filtered curve there is a small periodic disturbance of approximately 1 Hz. This can explain that the residuals is not white noise, it is hard to filter away this disturbance. This 1 Hz disturbance will be dealt with in the set-up.



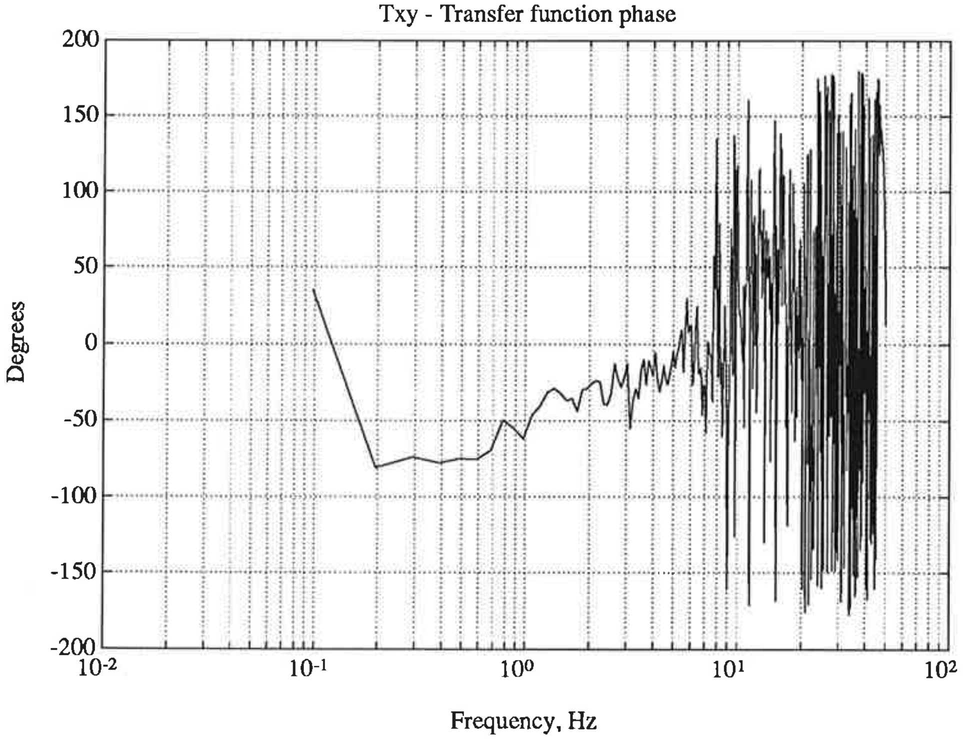


Figure 3.7 Bode-diagram based on the estimated transfer function which was obtained from frequency analysis on good filtered pressure and airflow signals, 6000 data points at 100 Hz. The digram is quite trustworthy in between 0.3-5 Hz outside this range it might be bad due to noise and the limited number of collected data points. This diagram should be compared to curve *a* in Fig. 3.6. They have the same behavior between 0.3-5 Hz.

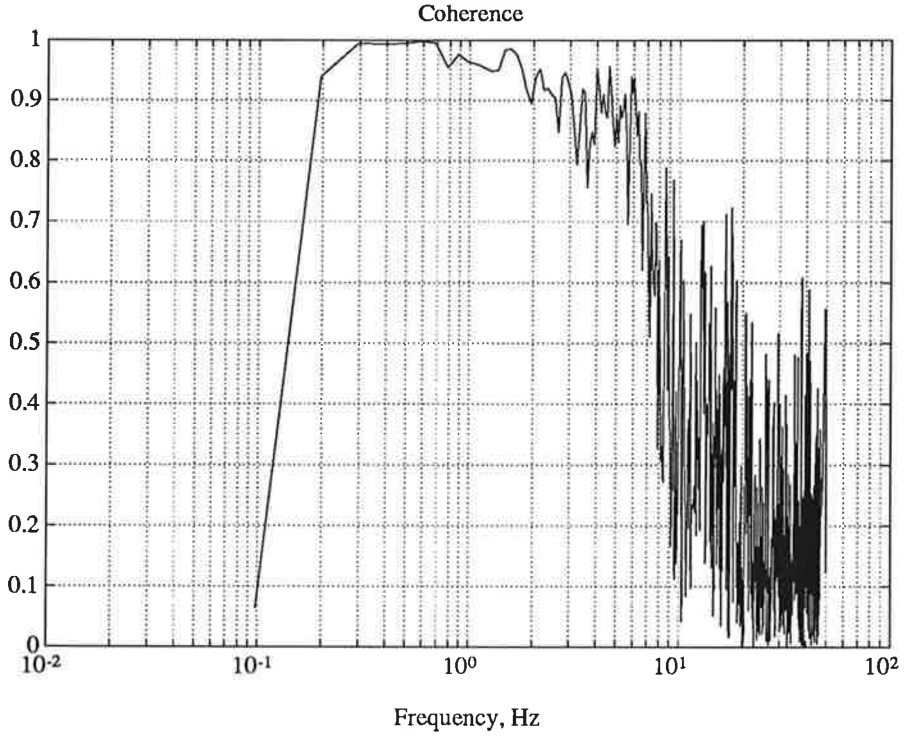


Figure 3.8 Coherence between pressure and airflow from a measurement sequence on a healthy sheep. There is good coherence between the signals up to 5 Hz, except for very low frequencies.

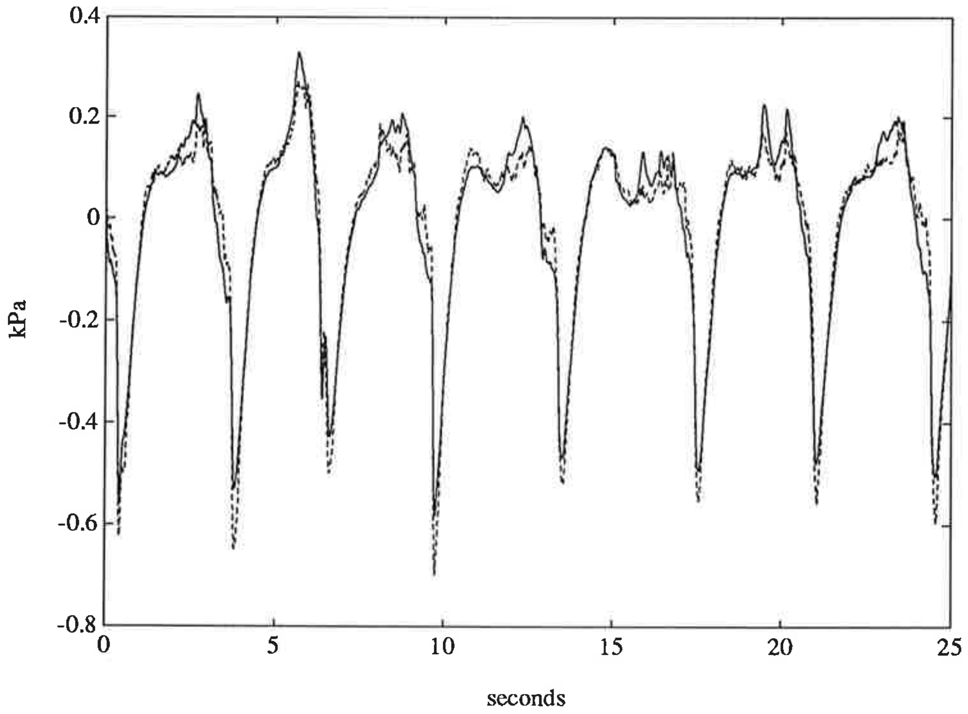


Figure 3.9 Validation of the model, Eq. 3.4. Estimates of parameter C and G has been used in the model on a sequence of data and a comparison has been made between the real output, solid lines, and the predicted pressure, dashed. They correspond quite well.

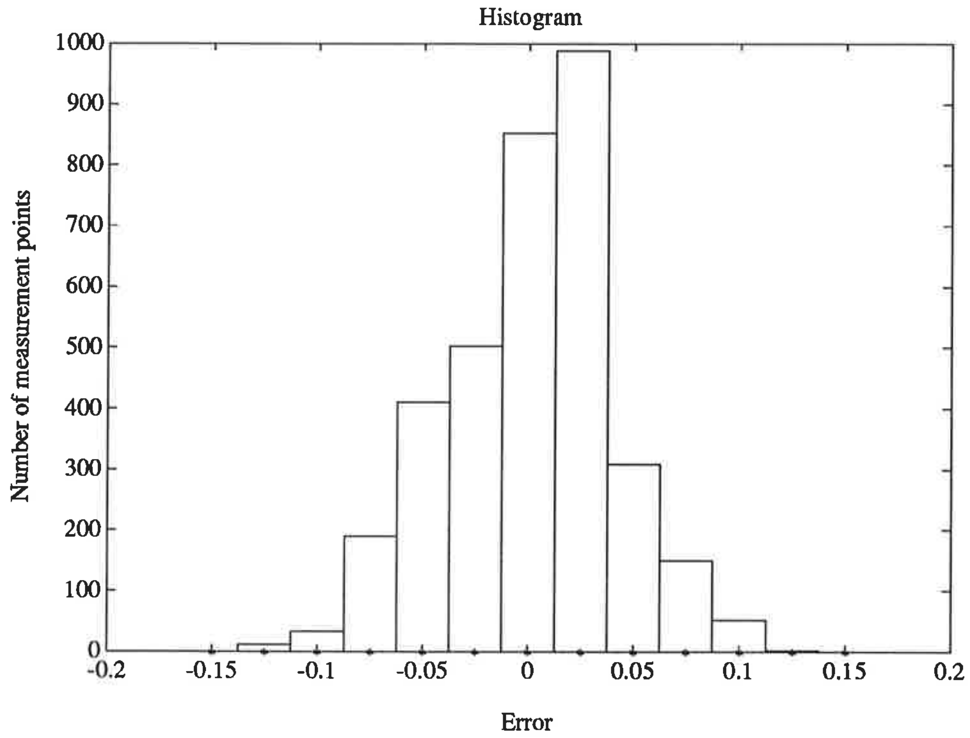


Figure 3.10 A histogram over the error between the predicted filtered pressure and the real filtered pressure from Fig. 3.9. It shows that the error is well gathered around zero. The amplitude of the real pressure was 0.8 kPa.

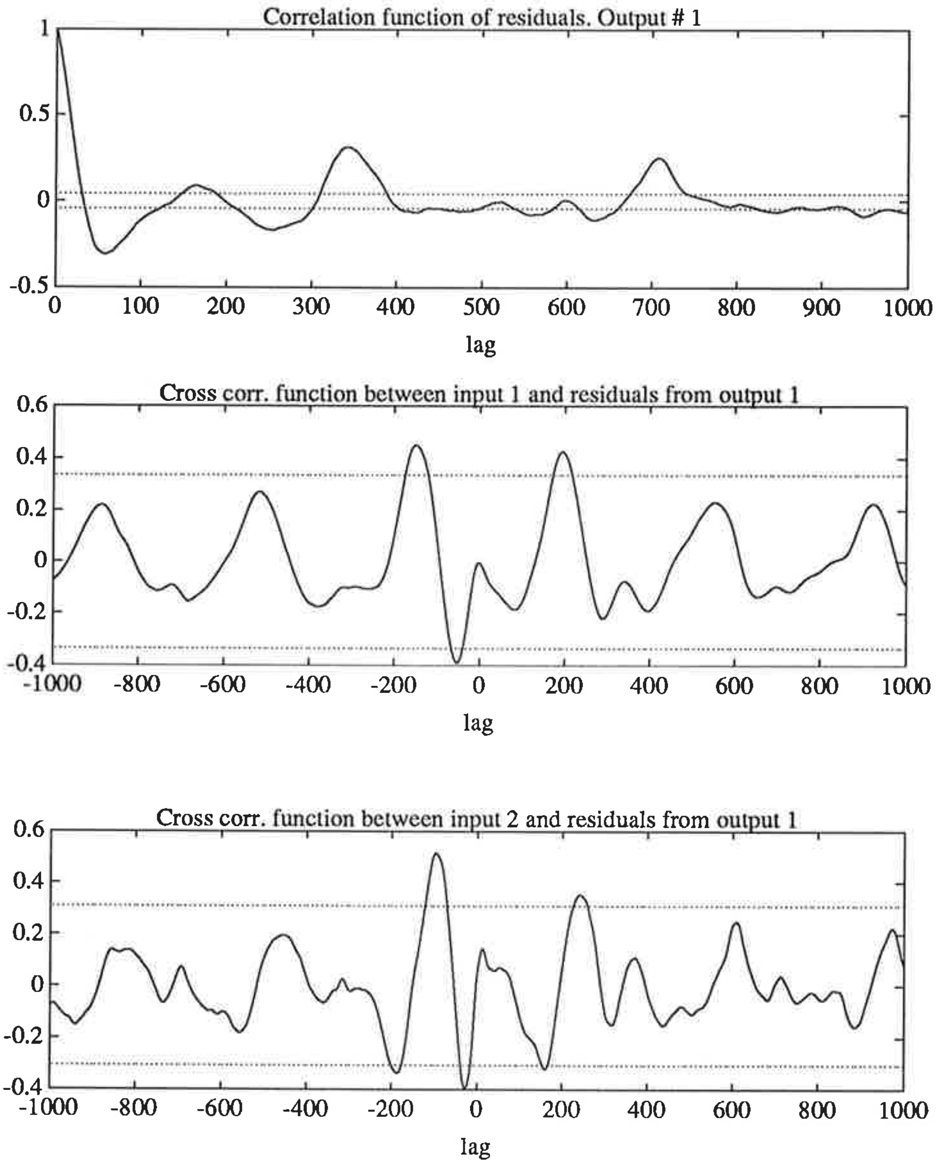


Figure 3.11 The upper figure shows the normalized correlation function of the pressure residuals based on the real and predicted pressure. The middle figure shows the cross correlation between input 1, volume, and the residuals. The lower figure shows the cross correlation between input 2, airflow, and the residuals.

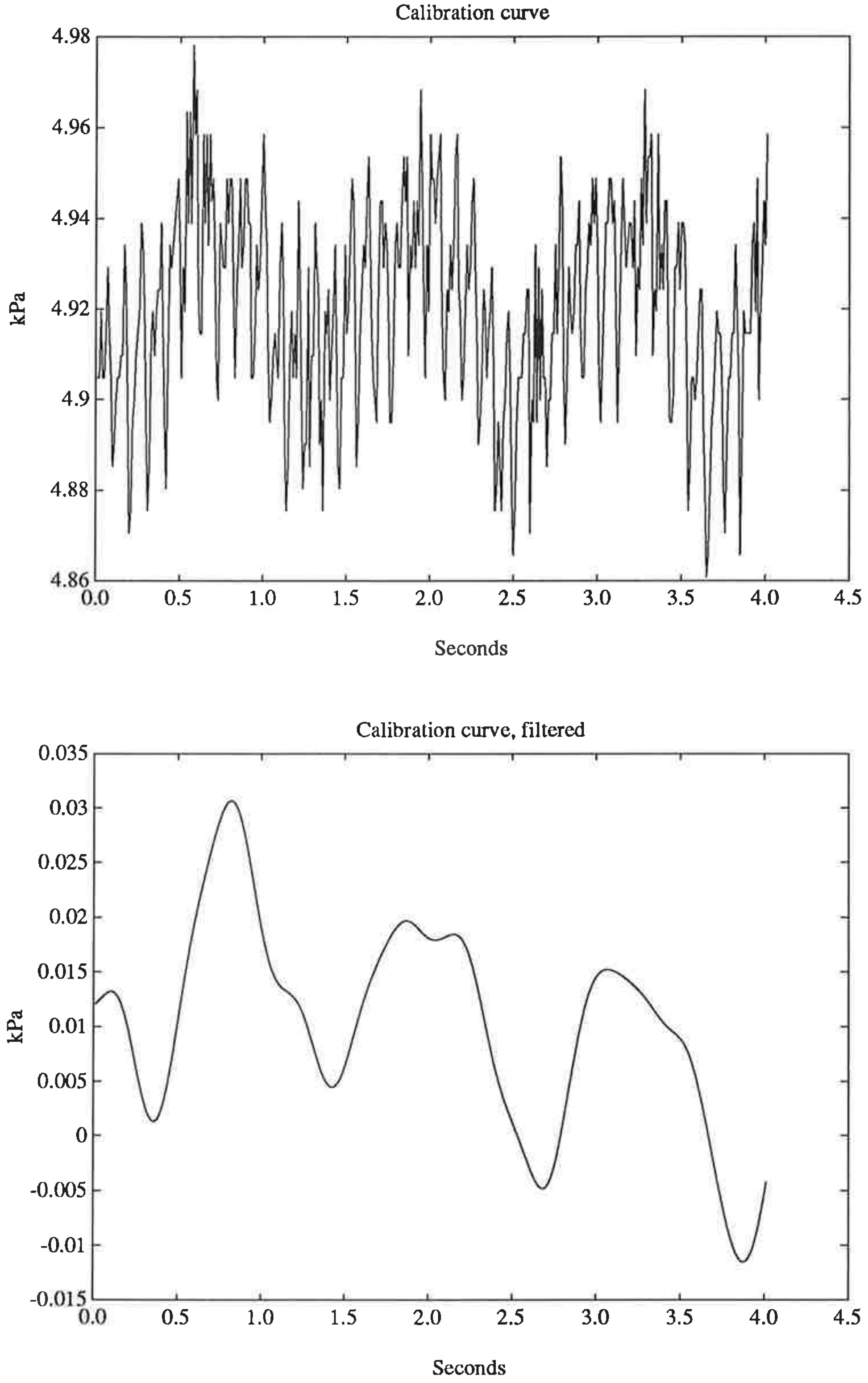


Figure 3.12 4 seconds of the pressure calibration curve ,which should be straight, where the upper one is the unfiltered signal and the lower one is the band-pass filtered signal. There is a small 1 Hz periodic disturbance present.

4. Estimation of respiratory parameters from sheep

This chapter shows estimation of C and G based on the new algorithm and compares it with the estimation done with the current estimation method at Draco.

4.1 Data without disturbances

The estimation done at Draco, using Eq. 3.3, is based on one good breathing cycle at the time. To decide if a breath is good or not some logic is used based on the volume as a reference. A breathing-cycle is used and one checks whether the volume starts and finishes at, approximately, the same value. Different criteria are used on these "volume values" that should be fulfilled before the breathing cycle is considered to be good, where a parameter estimation can be made.

Estimation made by using Eq. 3.3, without the ramp-term γ, is seen in Fig. 4.1 for the compliance, C, and in Fig. 4.2 for the conductance, G. In these figures the estimation from every breath is shown and a moving average based on these estimations, which will make it easier to compare the estimations from the least-square and the recursive least-square with each other. The moving average looks like

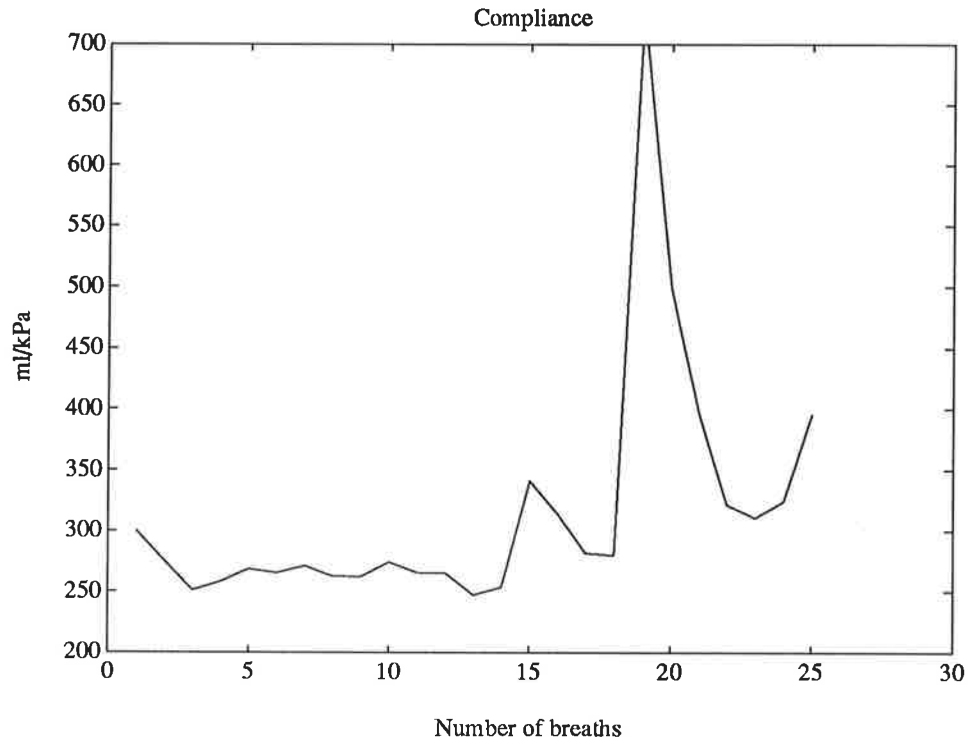
$$\bar{\theta}_k = \frac{1}{2}\bar{\theta}_{k-1} + \frac{1}{2}\hat{\theta}_k$$

where $\bar{\theta}_{k-1}$ is the average up to time $k-1$ and $\hat{\theta}_k$ is the value of $\hat{\theta}$ up to time k.

From the figures it can be seen that the estimates are rather jumpy. The compliance have a value between 250 ml/kPa and 700 ml/kPa and the conductance have a value between 1000 ml/(kPa*s) and 1900 ml/(kPa*s). Based on a measurement sequence like this, a mean value is calculated and the parameters are viewed as constant during the sequence time.

When using the recursive identification method all breaths has been taken into account. The estimation of the compliance and conductance can be seen in Fig. 4.3 – 4, these estimates are based on the same measurement sequence as Fig. 4.1-2. The estimation has, after curving inward lapse, found a value of the compliance, $C \approx$ 250 ml/kPa, and conductance, $G \approx$ 1700 ml/(kPa*s). These values seems to be the values the other method wanted to give as well, but had some difficulties to do. This is an indication, that the estimation of the interesting parameters, using recursive identification is good and more accurate. It also gives an easier way to say whether a breath is "good" or not.

The pressure and airflow was collected from a healthy sheep on the 20th of January 1992.



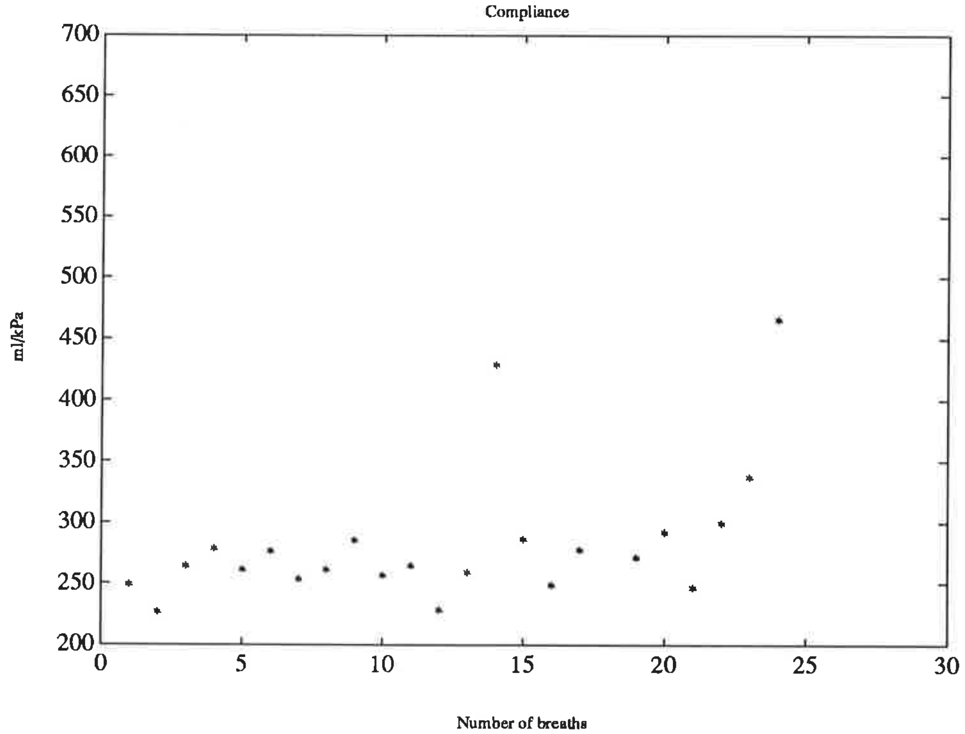
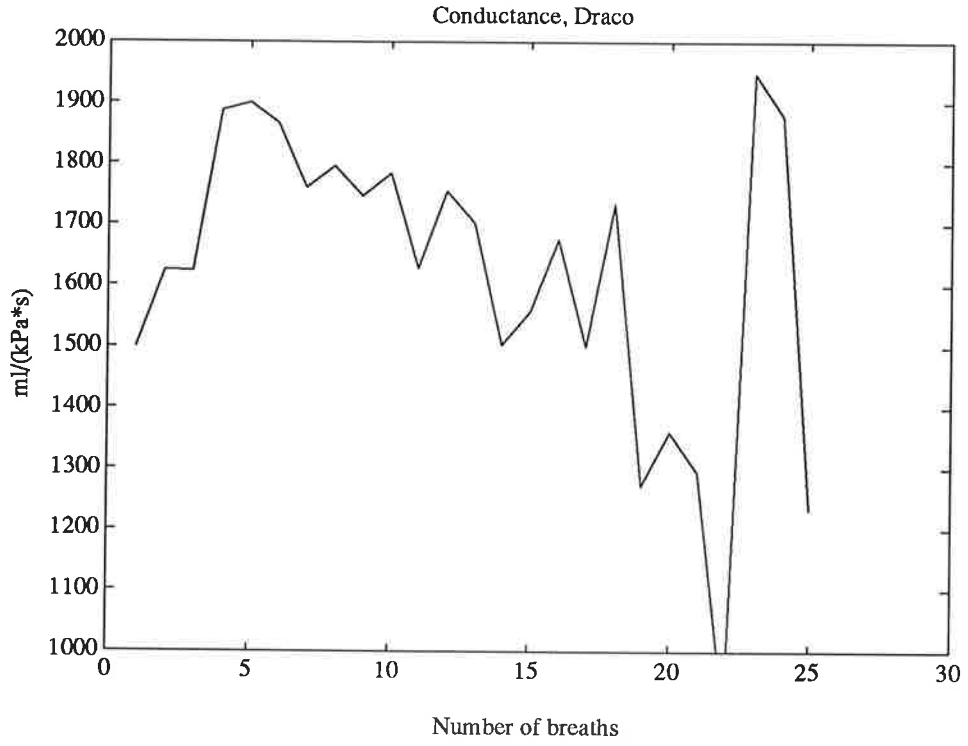


Figure 4.1 Compliance, C, estimated by using least-squares method. These estimates are calculated on one good breath, from a healthy sheep, at the time during four minutes. The lower figure shows every single breath estimate, breath number 18 and 25 are missing because they were too large. The upper plot shows the compliance estimates when a moving average has been used.



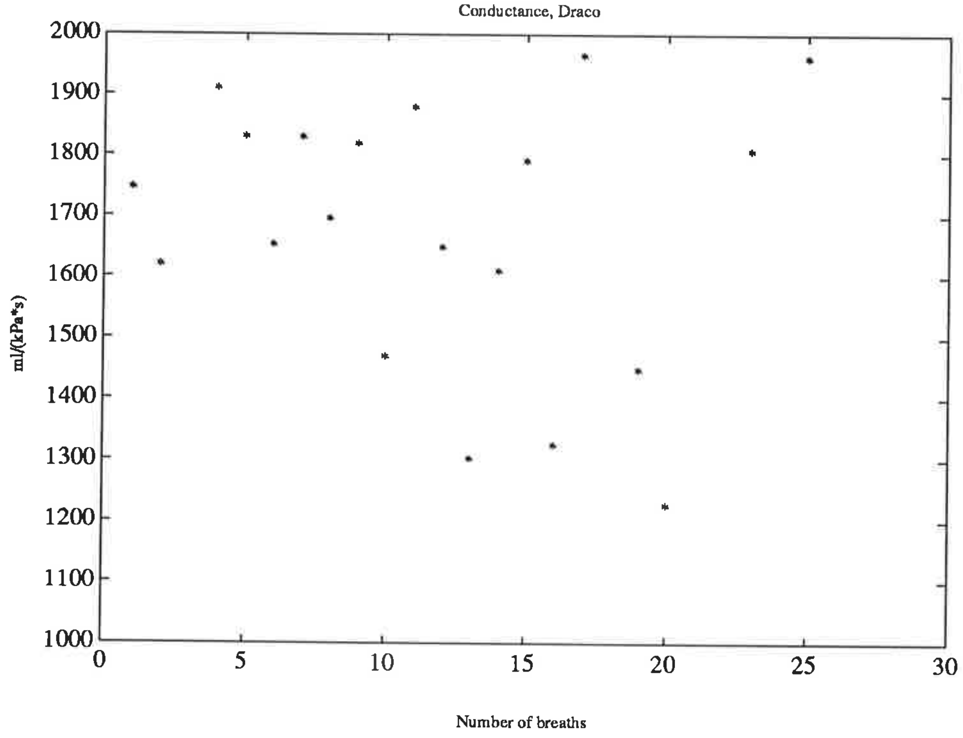


Figure 4.2 Conductance, *G*, estimated by using least-squares method. These estimates are calculated on one good breath, from a healthy sheep, at the time during four minutes. The lower figure shows every single breath estimate, breath number 3, 18, 21, 22 and 24 are missing because they were outside this scale. The upper shows the conductance estimates when a moving average has been used.

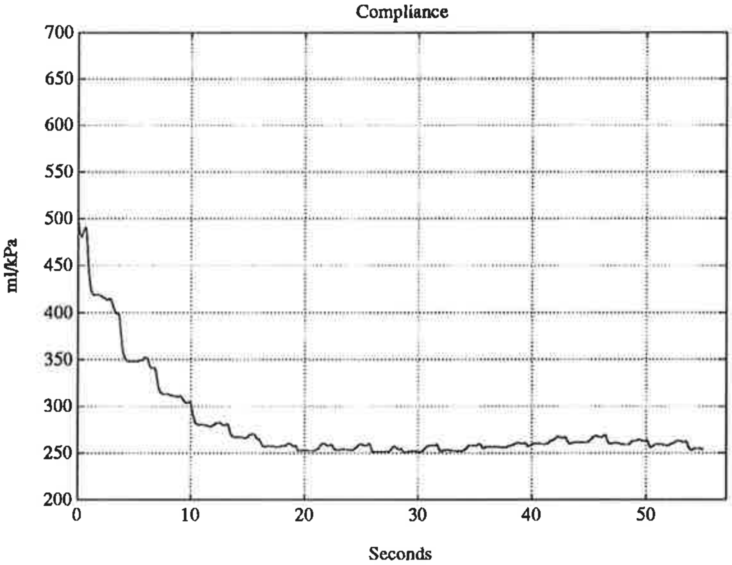


Figure 4.3 Compliance, C, estimated by using recursive least-squares method. This estimation is based on a breathing sequence without any disturbances and should be compared to Fig. 4.1 because the methods are estimating the same sequence of pressure, airflow and volume signals. The starting value of the parameter estimations has been set to a value somewhat away from the correct one just to be able to see the inward curve lapse of the estimator.

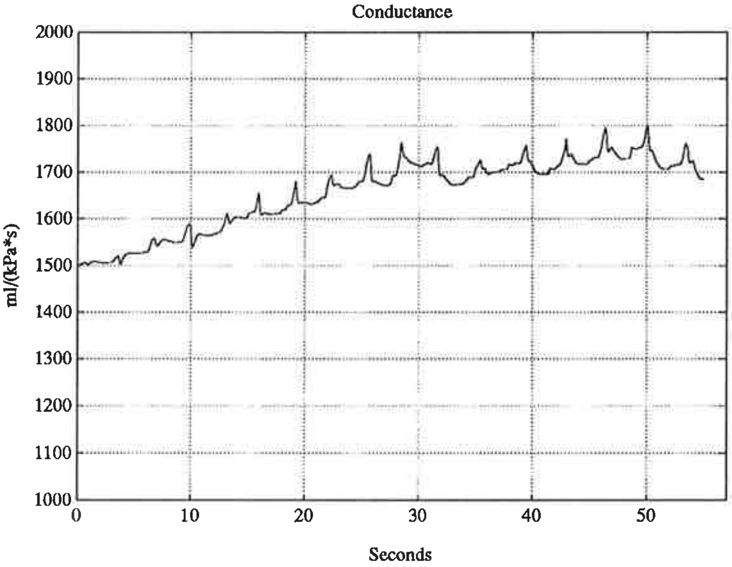


Figure 4.4 Conductance, G, estimated by using recursive least-squares method. This estimation is based on a breathing sequence without any disturbances and should be compared to Fig. 4.2 because the methods are estimating the same sequence of pressure, airflow and volume signals. The starting value of the parameter estimations has been set to a value somewhat away from the right one just to be able to see the inward curve lapse of the estimator.

4.2 Data with disturbances

Disturbance indicator

It has been shown in the previous section that algorithm Eq. 3.8 is capable of estimating the parameters C and G when there are no disturbances present. Looking at Fig. 2.2 there are however occasions with large disturbances in the pressure measurement. If algorithm 3.8 is used without modification, the parameters will become useless. To handle this situation so that algorithm Eq. 3.8 does not run into trouble when there is a disturbance present, there must be some kind of disturbance indicator. Since the disturbance is most obvious in the pressure the indicator will be pressure-based.

The indicator will make the algorithm Eq. 3.8 stop updating the breathing parameters and "freeze" the last good parameter value until the disturbance has past. When the algorithm starts again it will have the last good value to start the new updating of breathing parameters.

The indicator is prediction error based. This means that if the real pressure diverges from the predicted during some time, the updating will be turned off. The indicator is a first order filter:

$$e_k = \alpha * e_{k-1} + (1 - \alpha) * abs(p_m - p_k) \tag{4.1}$$

e_k = accumulated error
α = forgetting factor
p_m = measured pressure at time k
p_k = predicted pressure at time k

the forgetting factor, α, works like the forgetting factor λ. α was chosen as 0.95 after simulations.

It can be seen in Fig. 4.5 what the accumulated error, e_k, looks like, based on the pressure and airflow from Fig. 2.2 and Fig. 3.3. The criterion that should be fulfilled, without stopping the updating, is that the value of the accumulated absolute error, e_k, should be below a certain value. Typically in Fig. 4.5 this value should be 0.1 and when the accumulated error has decreased to a certain value the updating starts again.

Since the value of the accumulated error must be set to a value above the always present error between predicted and measured pressure, it means that the algorithm should be turned off some time before the disturbances is indicated. This is done simply by storing some data, so the "on-line" measurement are in practice delayed by 1-2 seconds. The way to do it is to have two different estimation algorithms like Eq. 3.8, where one is estimating online and the other makes a delayed estimation. Thanks to this, the "online-estimator" can tell the delayed estimator to stop the updating and let the disturbances pass by.

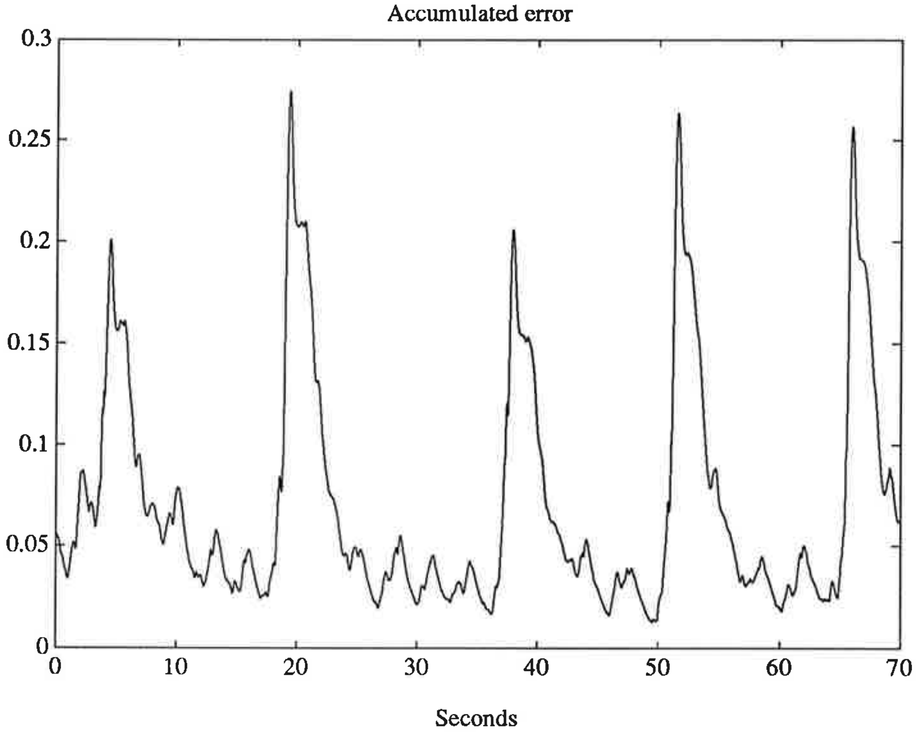


Figure 4.5 Accumulated error, e_k, calculated using Eq. 4.1. The peaks are indicating that the predicted output, pressure, differs from the real output, pressure. This means that there are outer disturbances acting on the system which makes Eq. 2.1 invalid. The peaks can be seen to correspond with the disturbances in the pressure curve from Fig. 2.2. When the accumulated error becomes too large the updating of the parameters is turned off.

Results

When using the recursive estimation method and the disturbance indicator on the pressure and airflow from Fig. 2.2 and 3.3 there was obtained estimations on compliance and conductance which can be seen in Fig. 4.6 and Fig. 4.7. The pressure and airflow has been collected from a healthy sheep on the 20th of January 1992. It can be seen that after 15 seconds of curving inward lapse the identifier has found the values of the parameters and the updating has been turned of five times during the estimation. Those five times are marked with an X in Fig. 2.2.

The estimator, Eq. 3.8 and 4.1, has also been tested on data that was collected during the trend measurement. The idea was to see if the estimator was capable of following time-varying parameters. Seven measurement sequences was collected, the first was made on a healthy sheep. Each sequence is separated where the $*$ are. Between the first and second sequence the sheep was exposed to a rather large dose of Methacoline, which make the bronchi contract. With the existing measurement set-up it is not possible to make any measurement while the sheep is exposed to asthma provoking substance. The sheep was exposed to Methacoline only once and then the sheep was recovering while the estimator was following the parameter variations.

Why there is more then two sequences is due to the limitations in the data collecting program. As said before the program can only store a certain amount of data and stored data had to be read over to the hard-disc, which cause a pause between two sequences of 200-300 seconds. During this pause

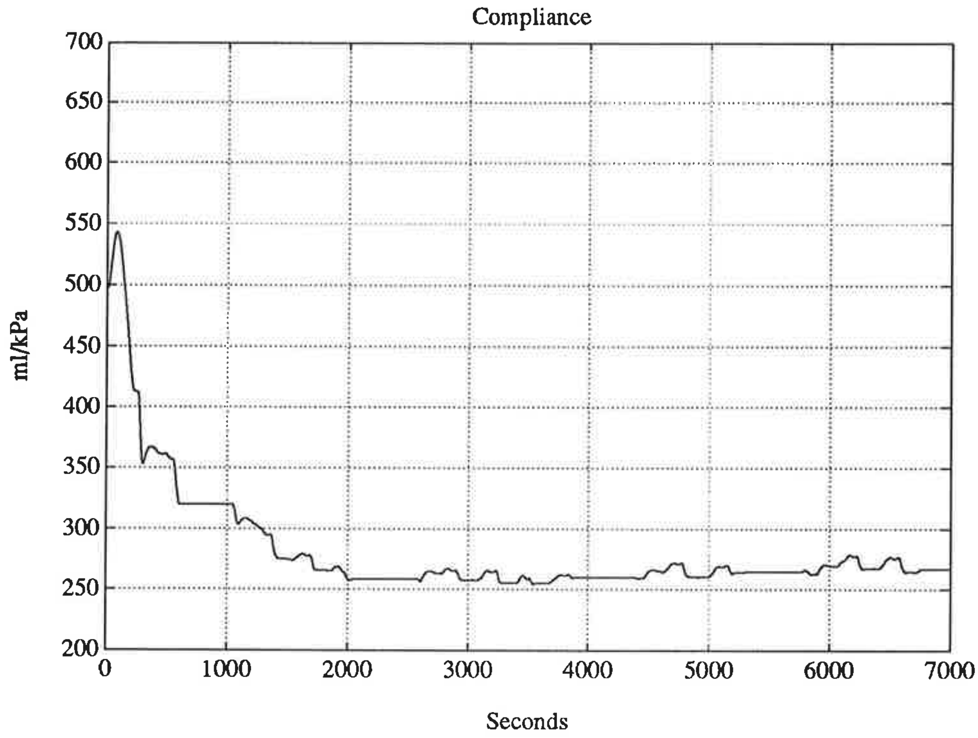


Figure 4.6 Compliance, C, estimated by using recursive least-squares method and disturbance indicator. Notice that the updating has been turned of five times when an outer disturbance acts on the system. This estimate is based on the measurement sequence in Fig. 2.2 and Fig. 3.3. This sequence is measured from a healthy sheep.

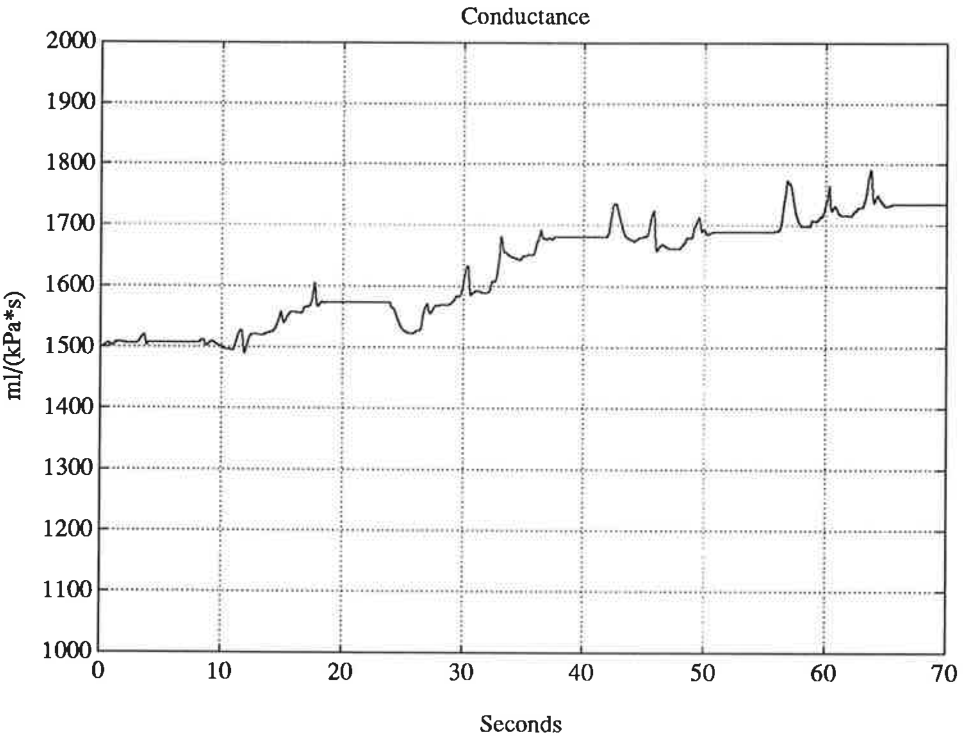


Figure 4.7 Conductance, G, estimated by using recursive least-squares method and disturbance indicator. Notice that the updating has been turned of five times when an outer disturbance acts on the system. This estimate is based on the measurement sequence in Fig. 2.2 and Fig. 3.3. This sequence is measured from a healthy sheep.

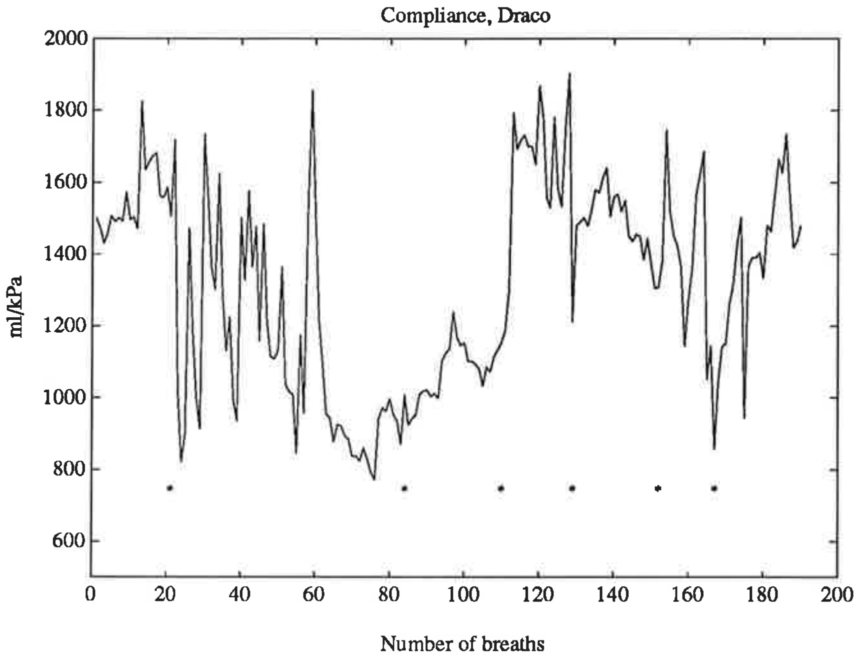


Figure 4.8 Compliance, C, estimated by using least-squares method. The points marked with an $*$ indicates that there has been a break in the measurement for $\approx$ 4-5 minutes due to limitations in the data collecting program. Between the first and second sequence the sheep has been exposed to a dose of Methacoline. This dose will make the values of C and G drop because Methacoline has bronchi-contracting effects and after a while the sheep will become healthier and healthier. These estimates should be compared to those in Fig. 4.10.

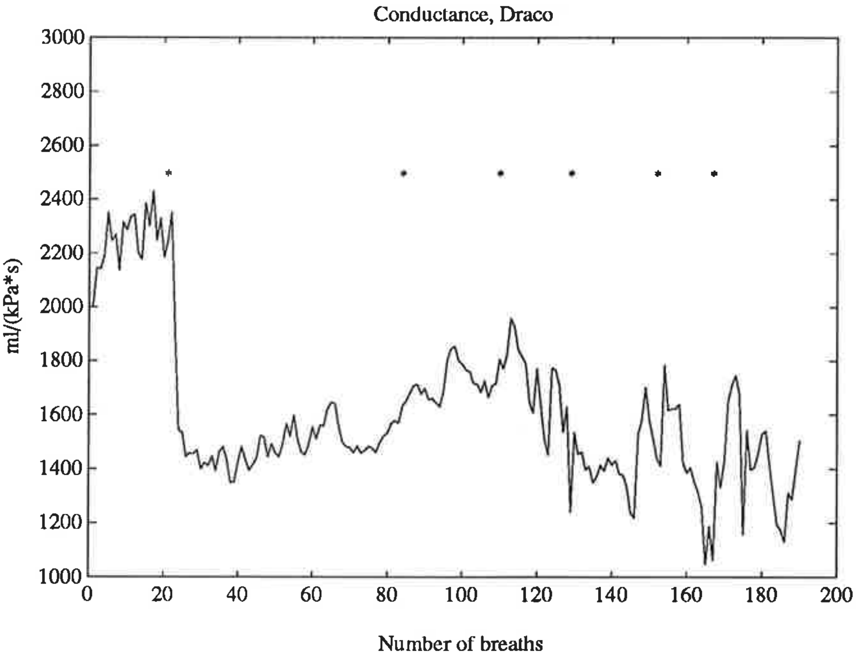


Figure 4.9 Conductance, G, estimated by using least-squares method. The points marked with an $*$ indicates that there has been a break in the measurement for $\approx$ 4-5 minutes due to limitations in the data collecting program. Between the first and second sequence the sheep has been exposed to a dose of Methacoline. This dose will make the values of C and G drop because Methacoline has bronchi-contracting effects and after a while the sheep will become healthier and healthier. These estimates should be compared to those in Fig. 4.10.

there was also happening things to the sheep.

The parameter-estimation done by Draco, can be seen in Fig. 4.8 and Fig. 4.9 in this figure the moving average mentioned earlier has been used. The estimation based on recursive least-squares method can be seen in Fig. 4.10.

The three last figures has got seven different measurement sequences, which are marked with an $*$. It can be seen in the first sequence that the sheep is healthy with a value of $C=$ 1600 ml/kPa and G $\approx$2300 ml/(kPa*s) when the Methacoline is added the values of the parameters are decreasing quite a lot but the conductance is decreasing before the compliance. This is probably due to the way that Methacoline is working, namely that it gives a reaction rather quickly in the bronchi which is closely connected to the conductance. During measurement sequence three the compliance is still at a rather low value while the conductance is striving upwards, meaning that the animal is getting healthier. From sequence four to seven the compliance is at a rather constant value, which can be considered to be at the "healthy" compliance-level. The conductance is going up and down during the four last sequences. This behavior is probably due to the behavior of Methacoline. It will give a contraction in the bronchi that will act for some time and affect the conductance while the lung and the compliance are only affected for a short time. It can be seen in figures 4.8-4.10 that both methods displays the same behavior of the parameter-estimations however the method is a bit jumpy, especially in the compliance estimates.

A sequence of 30 seconds between measurement 1 and 2 Fig. 4.10 is shown in detail in the following figures, 4.11-4.14. The pressure curve for the real pressure, solid line, and the predicted pressure, dashed line, can be seen in Fig 4.11. The figure shows that the sheep is breathing normally up to 14 seconds, when the Methacoline is added, after that a breathing of higher frequency occur due to contraction of the bronchi. Fig. 4.12-14 shows the corresponding accumulated error, estimated compliance and conductance in more detail.

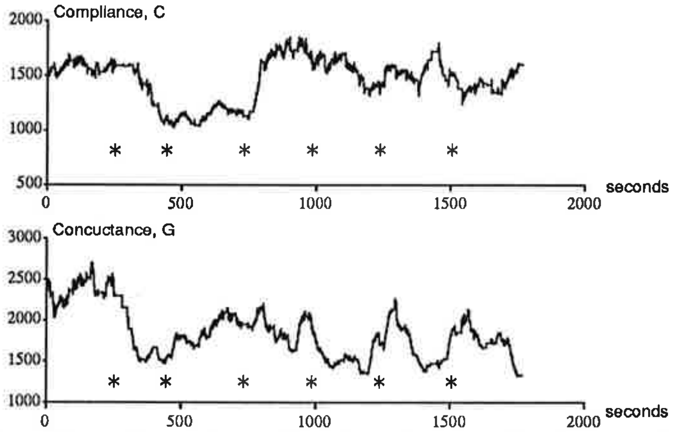


Figure 4.10 Estimated compliance, C, and conductance, G, using recursive least-squares method and disturbance indicator. The stars, $*$, are indicating that there has been a break in the measurement for $\approx$ 4-5 minutes due to limitations in the data collecting program. between the first and second sequence the sheep has been exposed to a dose of Methacoline. This dose will make the values of C and G drop because Methacoline has bronchi-contracting effects and after a while the sheep will become healthier and healthier. These estimates should be compared to those in Fig. 4.8 – 9.

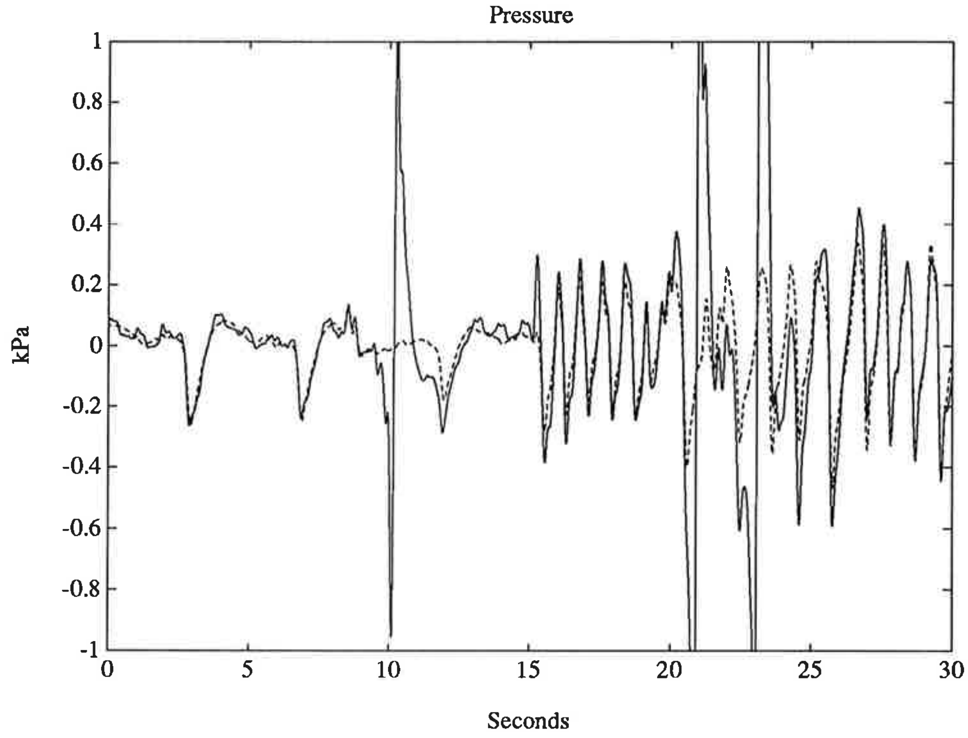


Figure 4.11 In this figure the solid line is the real pressure and the other the predicted pressure. At 14 seconds the sheep has been exposed to Methacoline and the breathing becomes faster due to the fact thats the animal has more difficulties to get enough oxygen. It can be seen in the figure that the model is following the real pressure value very well. Note that the model recovers well after the disturbances at 8-11 s and 20-23 s.

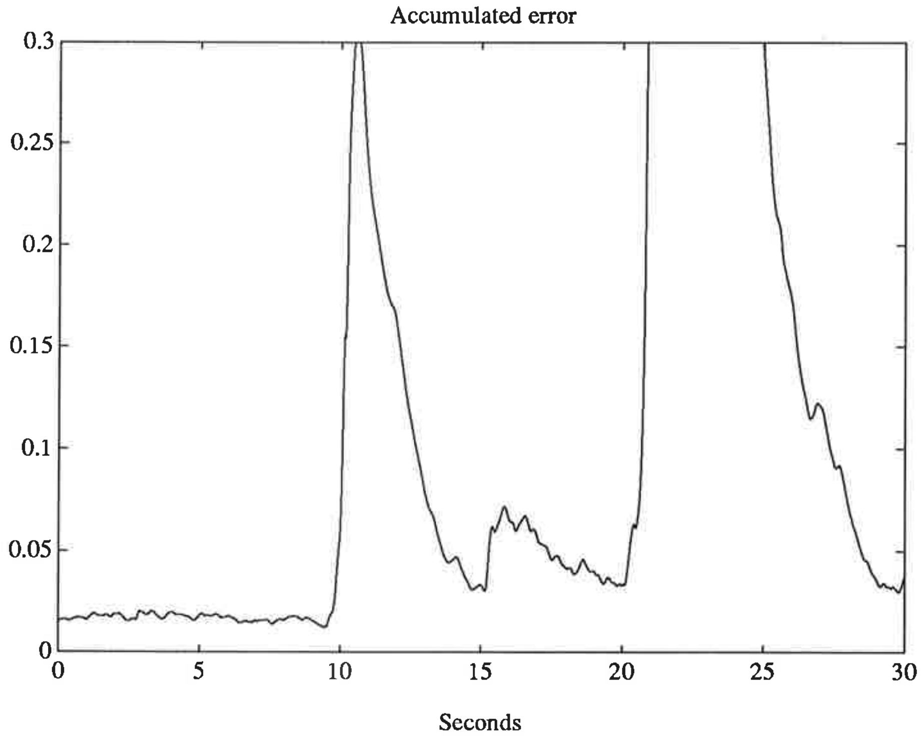


Figure 4.12 This is the corresponding accumulated error from the pressure curves in Fig. 4.11. The indicator has turned of the estimations in Fig. 4.12 – 13 when there are disturbances acting on the system.

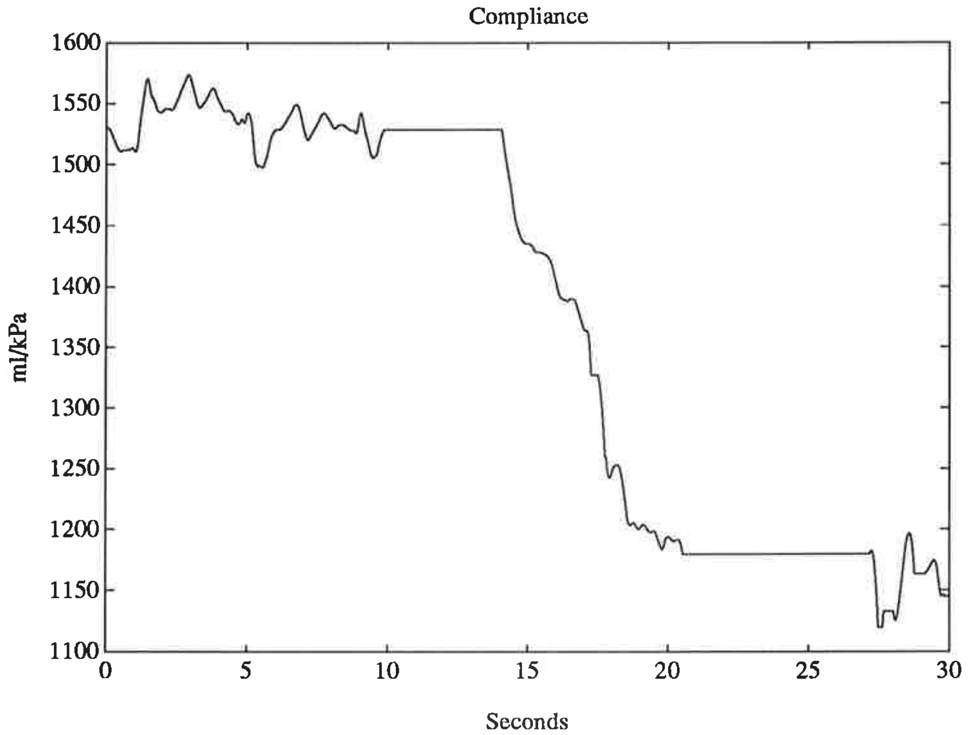


Figure 4.13 This is the corresponding estimation of the compliance, C, from the pressure curve in Fig. 4.11. The compliance value is slowly decreasing after the Methacoline-exposure. Note that the parameter converges to the new value in less than 10 s.

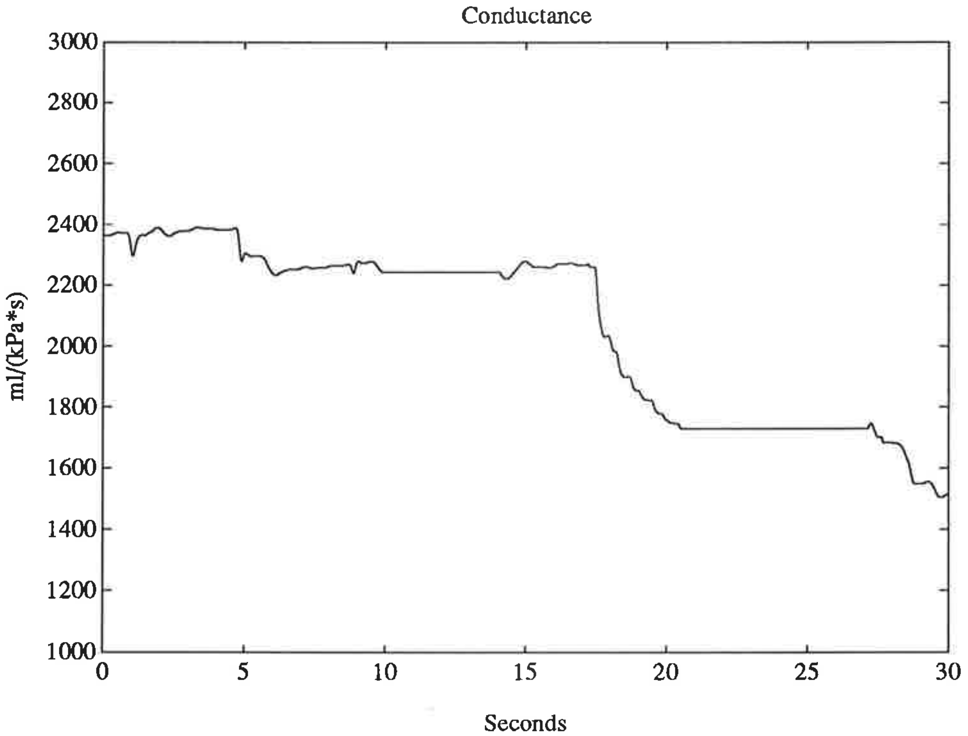


Figure 4.14 This is the corresponding estimation of the conductance, G, from the pressure curve in Fig. 4.11. There can be seen an effect on the conductance in this figure after the Methacoline-exposure, it is decreasing as expected. Note that the parameter converges to the new value in less than 10 s.

5. Discussion

Summary

There can be made some conclusion based on the facts from chapter 3 and 4.

When making an estimation when one of the signals, the volume, is an up-integration of the other used signal, air pressure, in the parameter estimation there should be taken into account that this will create an ramp in the up-integrated signal. A way to get rid of this ramp is simply by making a bandpass filtering of the signals, this gives a signal that is bias-free and will not create a ramp.

There has been made a check of the collected signals, pressure and airflow, and it has been found that the parametric dynamic lung model is giving the same Bode-diagram as a non parametric model, made from a frequency analysis. There has also been made a validation of the collected signals based on estimations of the parameters, C and G, this validation can be seen in Fig. 3.9. The coherence between pressure and airflow is very good up to 5 Hz this means that up to this frequency there can be made trustworthy estimations.

The recursive estimation method that was chosen to be used is the so called Kalman filter. This estimator has got the capability to estimate time-varying parameters. A disturbance indicator is used, that will turn off the estimator when something is wrong with the signals so that the model is not valid any more. In this way one can keep track of the parameters all the time which is not possible today. It is of course better to give the estimator initial values that is close to the real one but tests have shown that even if a value quite far away is chosen the estimater will only have a rather short curve inward lapse time, about 5 seconds.

A comparison of the estimates obtained with ordinary least-squares estimation and recursive estimation shows that the recursive estimation is more steady than the other method, see Fig. 4.8-10. Looking at the estimated parameters they show the same schematic behavior, going down and up at the same time but with the least-square being a bit more jumpy.

The recursive estimator is a good choice to make the parameter estimations. It has been shown that it is capable of following time-varying parameters and to handle outer disturbances like belching. One also avoids the difficult logic of deciding what is a "good breath".

Future research

A first order model gives as we have seen good correspondence to real data. It would however be interesting to try to find even better, more complex, models. It is for instance probable that different models should be used for inhalation and expiration. It can be seen from Fig. 3.11 that there is still correlation in the residuals, although there is only small correlation between residuals and regressors. This also indicates that a more complex model could be advantageous. This is left as an interesting future research project. The problem in Fig. 3.12 should first be investigated.

6. Implementation issues

MATLAB

The powerful software program MATLAB has been used in the analysis made in the earlier chapters. With the help of MATLAB the collected data has been investigated statistically and a validation of the model has been done, to see if the assumed model was a good representation of the real system. Based on this investigation a recursive calculation program has been written in MATLAB to see if it was possible to get an estimation of the parameters, see Appendix A. When it was found possible to estimate the parameters this recursive program was translated to SIMNON.

SIMNON

SIMNON is a software program which has been developed at the institution of Automatic control in Lund. The program can simulate dynamic systems using real input-signals, see Elmqvist and others(1990). It is possible to expand programs written in SIMNON to real-time SIMNON. By doing this it is possible to make the parameter-estimations on-line if the pressure and airflow signals are provided to the program.

SIM2DDC

To produce a more common used program language code a compiler called sim2ddc has been used. This compiler can compile and link the SIMNON code to a Modula-2 code which can make the same parameter-estimations as the SIMNON program but with real-time estimations, plotting of the parameters and a possibility to on-line change parameters like R, P, G and C. This Modula-2 code is command-driven.

The SIMNON code in Appendix A has been translated into Modula-2 code, using sim2ddc, which has been tested on an IBM-AT equipped with D/A- and A/D-converters. When testing the program on the computer it was capable of calculating parameter estimations, plotting them and changing all algorithm variables (P, R, G, C). There was a limitation in the speed which the computer was capable of sampling the signals, computing, plotting and to accept control-parameter changes when the program was running. This limit was about 25-30 Hz, the major reasons to this limit is that the computer is not very fast and that the Modula-2 code is automatically made which makes it very general and slower than if it had been written in the most optimal way. It should be mentioned that a delay of the signals in the SIMNON code can not be translated by the compiler into Modula-2 code. This is easily solved by just adding a vector or buffer in the Modula-2 code where the delayed elements can be stored.

Appendix. A

MATLAB and SIMNON-CODE

MATLAB

```
    Initialization routine
  h = 0.01; [B,A] = butter(6,0.4); "creating high-pass filtering
  p1 =korrP* bratryck(c:d);
  f1 =korrF* brafloede(c:d);
  p1 = filter(B,A,p1); "high-pass filtering
  f1 = filter(B,A,f1); "high-pass filtering
  b1=poly([1 1 1 1 1 1]); "creating low-pass filtering
  rootsa1 = exp(-0.01*pi/4*exp(i*pi/6*(-1:1/2.5:1)));
  a1 = real(poly(rootsa1));
  p1 = filter(b1,a1,p1); "low-pass filtering
  f1 = filter(b1,a1,f1); "low-pass filtering
  v1 = h*cumsum(f1); "integration of airflow z1 = [p1 v1 f1];
  z1 = z1(100:length); "compensation for transients in the digital filter
  "initial values
  th0 = [1/E 1/R ]; "E 200-1500, R 1000-2000
  p0 = [1e-6 0; 0 1e-6];
  R0 = [R11 0 ; 0 R22]; "R11 1e-9, R22 1e-10
  "Calling for the recursive estimator
  [thmx,yhatx] = recursive(z1,R0,th0,p0,niva,antal,procent);
  "antal 150, niva 0.15, procent 0.5
  thmx1=thmx(1:length(z1)-antal,1); "estimation of 1/C
  thmx2=thmx(1:length(z1)-antal,2); "estimation of 1/G
  yhatx = thmx.*z1(:,2:3); "estimated pressure
  yhatx = sum(yhatx')';
  thmx1 = thmx1.^-1; "getting hold of C, G
  thmx2 = thmx2.^-1;
  clg;
  "Plotting of the interesting parameters, C and G, accumulated error.
  subplot(221)
  "compliance
  axis([0 length(z1) 200 700])
  plot(thmx1(1:length(z1)-antal))
  grid
  "conductance
  axis([0 length(z1) 1000 2000])
  plot(thmx2(1:length(z1)-antal))
  grid
  "comparison between real and estimated pressure
  axis([0 length(z1) -1 1])
  plot([z1(:,1) yhatx]);
  grid
  "accumulated error
  e1=abs(z1(:,1)-yhatx);
```

```
axis([0 length(z1) 0 0.3])
a1=0.99;
ef1 = filter((1-a1),[1 -a1],e1); plot(ef1)
grid
hold off
axis('normal')
```

Recursive estimator

```
function [thmx,yhatx] = recursive(z,R0,th0,p0,niva,antal,procent)
[na,nb]=size(z);
p=p0; p1=p; th=th0; th1=th0;
aa=0.95; ff = 0; ff1 = 0; niva1=niva;
k=[1:na]; kk=k:
thmx=zeros(na,2);
yhatx=zeros(na,1);
phi=z(1:na,1:2); phi1=phi;
for k=1:na
"estimator one
yh=phi(k,:)*th';
epsi=z(k,1)-yh;
K=p*phi(k,:)'/(1 + phi(k,:)*p*phi(k,:)');
ff = aa*ff + (1-aa)*abs(epsi);
if ff < niva
th=th+K'*epsi;
p=(p-K'*phi(k,:)*p)+R0;
end
"estimator two
if k > antal
yh1=phi1(kk,:)*th1';
epsi1=z(kk,1)-yh1;
K1=p1*phi1(kk,:)'/(1+phi1(kk,:)*p1*phi1(kk,:)');
ff1 = aa*ff1 + (1-aa)*abs(epsi1);
if (( ff < niva1) and (ff1 < niva1))
niva1=niva;
th1=th1+K1'*epsi1;
p1=(p1-K1'*phi1(kk,:))*p1)+R0;
elseif ((th1 == thmx(kk-1,:)'))
niva1=niva*procent;
end
kk=kk+1;
thmx((kk,:)=th1'; yhatx(kk)=yh1;
end
k=k+1;
end
```

SIMNON-CODE *Macro koppla*

```
syst fileread rarx conn
default tsim=1770
```

```
store thmx11[rarx] thmx22[rarx]
split 2 1
simu 0 tsim // big
axes h 0 2000 v 500 2000
area 1 1
show thmx11
show thmx11
text'Compliance'
area 2 1
axes h 0 2000 v 1000 3000
show thmx22
text'Conductance'
end

discrete system fileread
time t
tsamp td
output flod pres
flod=rfile(airfl,t)
pres=rfile(press,t)
td=if tcol<0 then rfile(tcol,t) else t+dt
dt:0.01
tcol:0
airfl:2
press:3
end

discrete system rarx

input flod pres
"States for the filtering of the pressure,volume and airflow
state y1 y2 y3 y4 y5 y6
state x1 x2 x3 x4 x5 x6
state z1 z2 z3 z4 z5 z6
"States for integration to volume from airflow
state vol1
"States used in the recursive estimator
state thm1 thm2 p11 p22 p12 ff1 nival
State thm1r thm2r p11r p12r p22r ff1r
new ny1 ny2 ny3 ny4 ny5 ny6
new nx1 nx2 nx3 nx4 nx5 nx6
new nz1 nz2 nz3 nz4 nz5 nz6
new nvol1
new nthm1 nthm2 np11 np22 np12 nff nnival
new nthm1r nthm2r np11r np12r np22r nffr
time t
tsamp ts
"integrating the flow to get hold of the volume
volym=vol1 + h*flod
nvol1=volym

"Filtering of airflow, 3 second order filters
```

```
ny1=0.98847589319*y1+0.00613812678*y2+0.11973727144*flod
ny2=-0.00613812678*y1+0.99795831905*y2+0.02777096370*flod
Flodf=-0.11973727144205*y1+0.02777096370539*y2+flod
ny3=0.98735985206*y3+0.0059208574*y4+0.12397177212*flodf
ny4=-0.00592085741*y3+0.997934098*y4+0.02574783764*flodf
flodf1=-0.12397177212532*y3+0.02574783764667*y4+flodf
ny5=0.98666896469*y5+0.00578941095*y6+0.1265251350*flodf1
ny6=-0.00578941095*y5+0.99792732039*y6+0.02459461087*flodf1
flodf2=-0.12652513504754*y5+0.0245946108827*y6+flodf1

"Filtering of pressure, 3 second order filters
nx1=0.988475893190*x1+0.00613812678*x2+0.11973727144*pres
nx2=-0.00613812678*x1+0.99795831905*x2+0.02777096370*pres
presf=-0.11973727144205*x1+0.02777096370539*x2+pres
nx3=0.98735985206*x3+0.0059208574*x4+0.12397177212*presf
nx4=-0.00592085741*x3+0.997934098*x4+0.02574783764*presf
presf1=-0.12397177212532*x3+0.02574783764667*x4+presf
nx5=0.98666896469*x5+0.00578941095*x6+0.1265251350*presf1
nx6=-0.0057894109*x5+0.99792732039*x6+0.02459461087*presf1
presf2=-0.12652513504754*x5+0.0245946108827*x6+presf1

"Filtering of volume, 3 second order filters
nz1=0.988475893196*z1+0.006138126788*z2+0.119737271441*volym
nz2=-0.006138126788*z1+0.997958319056*z2+0.027770963706*volym
volymf=-0.119737271442*z1+0.027770963705*z2+volym
nz3=0.987359852065*z3+0.00592085741*z4+0.123971772125*volymf
nz4=-0.005920857410*z3+0.9979340987*z4+0.025747837646*volymf
volymf1=-0.123971772125*z3+0.025747837646*z4+volymf
nz5=0.986668964690*z5+0.005789410952*z6+0.12652513504*volymf1
nz6=-0.005789410951*z5+0.997927320395*z6+0.024594610879*volymf1
volymf2=-0.126525135047*z5+0.02459461088*z6+volymf1

"Using two sets off regressors where one is delayed to be able to stop
"the updating of the parameters if an outer disturbance is acting on
"the system
volym3=delay(volym,0.01)
flodf3=delay(flodf2,0.01)
presf3=delay(presf2,0.01)
volym4=delay(volym3,tid)
flodf4=delay(flodf3,tid)
presf4=delay(presf3,tid)

"Correction of the signals so the parameter value will be physically
"right
flodx=korrF*flodf3
presx=korrP*presf3
volymx=korrF*volym3
flor=korrF*flodf4
volr=korrF*volym4
prer=korrP*presf4

"First recursive estimator
```

```
tryck=volymx*thm1+flodx*thm2
epsi=presx-tryck
w11=p11*volymx+p12*flodx
w12=p12*volymx+p22*flodx
den=w11*volymx+w12*flodx+1
k11=w11*epsi/den
k22=w12*epsi/den
nff=ff
ff=aa*ff1+(1-aa)*abs(epsi)
thmx1=if ff<niva then (thm1+k11) else thm1
thmx2=if ff<niva then (thm2+k22) else thm2
px11=if ff<niva then (p11-w11*w11/den+R11) else p11
px12=if ff<niva then (p12-w11*w12/den+R12) else p12
px22=if ff<niva then (p22-w12*w12/den+R22) else p22
nthm1=thmx1
nthm2=thmx2
np11=px11
np12=px12
np22=px22

"Second recursive estimator
tryckr = volr*thm1r + flor*thm2r
epsir = prer - tryckr
wr11 = p11r*volr + p12r*flor
wr12 = p12r*volr +flor*p22r
denr = wr11*volr + wr12*flor + 1
kr11 = wr11*epsir/denr
kr22 = wr12*epsir/denr
nffr = ffr
ffr = aa*ff1r + (1-aa)*abs(epsir)
och = (ffr<niva1) and (ff<niva1)
niva1r = if och then niva else (proc*niva)
thmx1r = if och then (thm1r+kr11) else thm1r
thmx2r = if och then (thm2r+kr22) else thm2r
px11r = if och then (p11r-wr11*wr11/denr+R11) else p11r
px12r = if och then (p12r-wr11*wr12/denr+R12) else p12r
px22r = if och then (p22r-wr12*wr12/denr+R22) else p22r
nthm1r = thmx1r
nthm2r = thmx2r
np11r = px11r
np12r = px12r
np22r = px22r
nniva1 = niva1r

"The interesting parameters thmx11=compliance thmx22=conductance
thmx11=1/thmx1r
thmx22=1/thmx2r
ts=t+h

"Control parameter values
niva:0.06
niva1:0.06
```

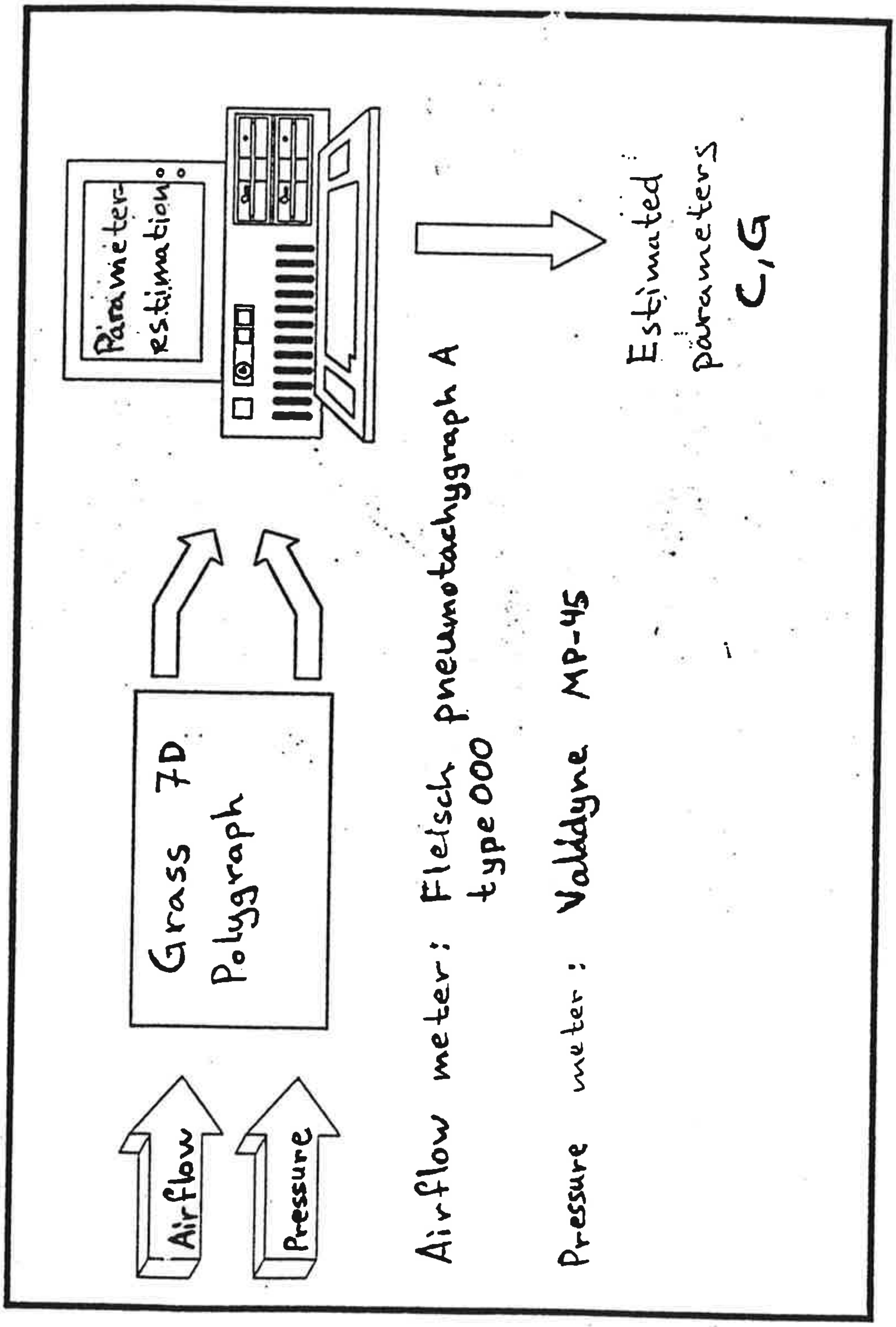
```
tid:3
proc:0.5
R11:1e-10
R12:0
R22:4e-11
aa:0.95
korrP:0.61157
korrF:245.7527
h:0.01
vol1:0
thm1:0.0006666
thm2:0.0004
thm1r:0.000666
thm2r:0.0004
p11:1e-7
p22:1e-7
ff1:0
p11r:1e-7
p22r:1e-7
ff1r:0
end
```

connecting system conn

```
time t
flod[rarx]=flod[fileread]
pres[rarx]=pres[fileread]
end
```

Appendix. B

EXPERIMENTAL SET-UP



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