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Real Time Modelling of Flow Systems

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MASTEROPPGAVE

for

Stud.techn. Sigrid Marie Skodje

Våren 2013

Sanntids modellering av strømningssystemer

Real time modelling of flow systems

Bakgrunn og målsetting

I prosjektoppgaven har kandidaten undersøkt kavitasjonsforhold i pumper og hvilke faktorer som påvirker dette. Det er blitt diskutert hvordan ulike typer væsker oppfører seg ved kavitasjonsdannelse og hvordan det påvirker erosjon og kavitasjonsdannelse. Et LabVIEW program er laget for å analyser målinger for kavitasjonsdeteksjon. Programmet ble benyttet ved analyse av måledata fra en vannkraftstasjon og fungerte svært tilfredsstillende.

I et parallelt phd studium utvikles tilsvarende programvareløsning for sanntidssystemer basert på FPGA og LabView realtime moduler. I tillegg er det økende interesse for å bruke sanntids modellering av strømningssystemer blant annet som tilstandskontroll. På bakgrunn av nivået som er oppnådd i løpet av prosjektperioden er det naturlig at studenten fortsetter arbeidet med å lage en sanntids modellering av et strømningssystem og demonstrerer dette i et enkelt laboratorieforsøk.

Oppgaven bearbeides ut fra følgende punkter:

1 Litteraturstudium på dynamisk modellering og kontroll av strømningssystemer.
2 Utforme og bygge en passende laboratorieoppstilling.
3 Utvikle LabView sanntids programvare for modellering, måling og kontroll.
4 Gjennomføre målinger for demonstrasjon av programmet.

Senest 14 dager etter utlevering av oppgaven skal kandidaten levere/sende instituttet en detaljert fremdrift- og eventuelt forsøksplan for oppgaven til evaluering og eventuelt diskusjon med faglig ansvarlig/veiledere. Detaljer ved eventuell utførelse av dataprogrammer skal avtales nærmere i samråd med faglig ansvarlig.

Besvarelsen redigeres mest mulig som en forskningsrapport med et sammendrag både på norsk og engelsk, konklusjon, litteraturliste, innholdsfortegnelse etc. Ved utarbeidelsen av teksten skal kandidaten legge vekt på å gjøre teksten oversiktlig og velskrevet. Med henblikk på lesning av besvarelsen er det viktig at de nødvendige henvisninger for korresponderende steder i tekst, tabeller og figurer anføres på begge steder. Ved bedømmelsen legges det stor vekt på at resultatene er grundig bearbeidet, at de oppstilles tabellarisk og/eller grafisk på en oversiktlig måte, og at de er diskutert utførlig.

Alle benyttede kilder, også muntlige opplysninger, skal oppgis på fullstendig måte. For tidsskrifter og bøker oppgis forfatter, tittel, årgang, sidetall og eventuelt figurnummer.

Det forutsettes at kandidaten tar initiativ til og holder nødvendig kontakt med faglærer og veileder(e). Kandidaten skal rette seg etter de reglementer og retningslinjer som gjelder ved alle (andre) fagmiljøer som kandidaten har kontakt med gjennom sin utførelse av oppgaven, samt etter eventuelle pålegg fra Institutt for energi- og prosessteknikk.

Risikovurdering av kandidatens arbeid skal gjennomføres i henhold til instituttets prosedyrer. Risikovurderingen skal dokumenteres og inngå som del av besvarelsen. Hendelser relatert til kandidatens arbeid med uheldig innvirkning på helse, miljø eller sikkerhet, skal dokumenteres og inngå som en del av besvarelsen. Hvis dokumentasjonen på risikovurderingen utgjør veldig mange sider, leveres den fulle versjonen elektronisk til veileder og et utdrag inkluderes i besvarelsen.

I henhold til "Utfyllende regler til studieforskriften for teknologistudiet/sivilingeniørstudiet" ved NTNU § 20, forbeholder instituttet seg retten til å benytte alle resultater og data til undervisnings- og forskningsformål, samt til fremtidige publikasjoner.

Besvarelsen leveres digitalt i DAIM. Et faglig sammendrag med oppgavens tittel, kandidatens navn, veileders navn, årstall, instituttnavn, og NTNUs logo og navn, leveres til instituttet som en separat pdf-fil. Etter avtale leveres besvarelse og evt. annet materiale til veileder i digitalt format.

☐ Arbeid i laboratorium (vannkraftlaboratoriet, strømningsteknisk, varmeteknisk)
☐ Feltarbeid

NTNU, Institutt for energi- og prosessteknikk, 14. januar 2013

Olav Bolland
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Preface

This thesis is written at the Water Power Laboratory, Institute for Energy and Process at NTNU spring 2013, and is written in collaboration with Flow Design Bureau. The thesis will cover real time modeling of flow systems, and how to incorporate this in LabVIEW.

I would like to use this opportunity to thank my supervisors Torbjørn Nielsen and Morten Kjeldsen for competent guidance and counseling. I also want to thank the employees of FDB, Håkon H. Francke and Jarle V. Ekanger for their competence and help.

Further i would like to thank the employees of the Water Power Lab for great help with the modification of the rig and the experiments.
Last, but not least, i would like to thank the PhDs and student at the lab for all the help and the god times.

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Sigrid Marie Skodje

Abstract

Hydro power plants are operated in a different manner than what they used to be, due to increased focus on economy, and less on operating on best efficiency point. This creates new challenges related to wear and tear of the plant. In order to maintain and avoid degradation, the need for control is increased. Installing sensors in a hydro power plant may be difficult, and modeling and estimating parameters could be a solution. This thesis will cover real time modeling of flow systems, with particular focus on the Kalman filter. The filter is an important part of control engineering, but the utilization in hydro power seems to be limited. The goal of this thesis is to understand how the Kalman filter works for hydro power applications, and how it can be implemented in LabVIEW.

The Kalman filter investigated is the nonlinear Discrete Extended Kalman filter. The case chosen is the estimation of flow, based on two different pressure losses. The Kalman filter program was run at different operating points in order to investigate the filters function on the dynamics of the system.

The experimental rig used was the existing Swirl rig at the Water Power lab at NTNU. Some modifications had to be made in order for the rig to fit the experiment specifications. One of the main valves were changed, and some extra pressure outlets were made. Both flowmeters, absolute pressure transducers and differential pressure transducers were used for the experiment, all of these calibrated by the calibration program presented. The calibration includes uncertainty analysis.

Both the calibration program and the Kalman filter program is presented step by step in order to describe the features and logic behind the programming.

The main part of the results seemed to coincide with the Kalman filter theory. The estimations of the flow based on pressure loss over the valve seemed to follow the measured values, but the estimations for the pressure loss over the swirl generator did not. Some of the estimations showed reduction in loss compared to the measurements. These and more results are presented and discussed.

Sammendrag

Vannkraftverk blir driftet annerledes nå enn før i tiden. Fokuset har gått fra å kjøre på best mulig virkningsgrad til å ha et overveiende fokus på økonomi. Dette skaper utfordringer både med tanke på vedlikehold og slitasje, men også økt fokus på overvåkning av kritiske parametere. Installering av sensorer og volumstrømsmålere i et vannkraftverk kan være både vanskelig og økonomisk utfordrede, og dette fører til økt fokus på andre metoder. Modellering av vanskelige parametere er muligens en løsning. Denne oppgaven vil omhandle sanntids modellering av strømningssystemer med spesielt fokus på Kalman-filteret, og hvordan dette kan implementeres i LabVIEW. Kalmanfilteret er en viktig ressurs i moderne reguleringsteknikk, dog er bruken innen vannkraftbransjen begrenset. Målet med denne oppgaven er å forstå hvordan Kalmanfilteret fungerer på vannkraftrelaterte problemstillinger, og hvordan dette kan implementeres i LabVIEW.

Det Kalmanfilteret som er brukt er det ikke-lineære "Discrete extended Kalman filter". Det blir forsøkt modellert volumstrøm ut i fra to forskjellige trykktap. Programmet ble kjørt på flere ulike driftspunkt for å undersøke den dynamiske responsen i modellen.

Riggen som ble brukt i oppgaven er den eksisterende Swirl-riggen som står på Vannkraftlaboratoriet på NTNU. Det har blitt gjort noen modifikasjoner for å få den til å passe til eksperimentet. En av hovedventilene ble endret og ekstra trykkuttak er sveist ut. Både volumstrømsmålere, absolutt trykktransdusere og differensial-trykkstransdusere er brukt, og de er kalibrert med kalibreringsprogrammet som er beskrevet. Kalibreringen

inneholder også en usikkerhetsanalyse.

Både kalibreringsprogrammet og Kalman-filter programmet er presentert steg for steg for å forklare funksjonene og logikken bak programmeringen.

Resultatene fra eksperimentet virker å sammenfalle med teorien om Kalman-filteret. Estimeringen av volumstrømmen basert på trykktap over ventil ser ut til å følge de målte verdiene godt, men volumstrømmen basert på trykktap over swirlgeneratoren gjør det ikke. Noen av estimatene viser tegn på redusert støy i forhold til målingene. Disse og flere resultater er presentert og diskutert.

Scope

There are many ways of modeling a flow system. For the current work the Kalman filter has been chosed. The method is widely used in control engineering, but not so much in the hydro power industry. The method is suited for real time applications, and is available in the LabVIEW control and simulation package.

The filter is relatively easy to implement, but can be cumbersome to debug, due to no error handling in the LabVIEW function, and this can make small errors time-consuming to find.

The measurements and modeling were conducted with a LabVIEW program on a RIO (Reconfigurable input/output). Originally a single board evaluation kit RIO was to be used for the experiments. Due to few input terminals, the SbRIO was swapped with an older compact RIO. Later the some of the application in the Kalman filter program proved difficult to deploy on the cRIO, and the single board RIO had to be used after all. Due to the few input terminals, the number of sensors had to be reduced to 6. This resulted in a change in the test-case and modifications to both the program and the experiment. This meant that many of the sensors calibrated were not really used and that the calibration was conducted through the wrong RIO. It also meant extra work to convert all the ampere signals to voltage signals and redo the setup in the rig.

Connecting to the RIO is supposed to be a smooth operation, but connection issued proved to be somewhat challenging. Some of it was due to the age of the cRIO, but software issues, the RIOs operating system and the firewalls on the computer were not all that innocent either. A lot of time was used figuring out connection issues.

The rig had to be modified to fit the project specification. More pressure outlets were made, and the back-pressure valve had to be changed to one that was controllable from the 2.floor. The work on the valve was delayed by quite some time, and resulted in a large delay on both the calibration and the experiments. In addition the pressure sensors that were used had to be shared with another project that was delayed several times, which delayed this experiment even further. The result was that the experiment was done at the very end of the semester, and that the time for both tuning and experimenting with variables, in addition to post processing of the results were limited.

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Chapter 1

Introduction

The increasing pressure on the energy sector results in higher demand for efficient and flexible solutions. Power station are often operated based on economy, which implies more operation off best efficiency point. This increases the wear and tear on the power plant, and so the need for control of critical parameters increases. A real time monitoring system with permanently installed sensors allows a continuously overview of the states in the hydro power plant. Methods that can give reliable estimates could improve the way that power stations are run, which could result in both more efficient solutions and better usage of the water recourses.

For simulations of hydro power problems the accuracy of the model is of great importance, but in order to model the reality, an extreme amount of computer capacity would be needed. Therefore the models are normally somewhat inaccurate, in order to be solvable. The imperfections in the model may lead to errors in the results, and when simulating for some time, even small imperfections may escalate. A filter that is able to ”catch up” with reality by using real measurements will improve the results dramatically.

The Kalman filter is an estimator that estimate values based on both the mathematical model and measurements. If the systems redundancy and observability is high it can both estimate accurate values, monitor sensor function and remove noise from measurement values. It also has good implementation with real time systems due the fact that the only values needed are the measurements value and the previous states. This implies that the method does not require large data storage or have to do calculations on large data sets.

The relatively new technologies and good computer capacity in modern RIOs enables the possibility to run a stand alone modeling program in real time.

Implementing a good modeling and control system may result in a more efficient way of gaining control of the power plant. Estimated values are found, malfunctioning sensors are discovered, and uncertainties reduced. The result will be better use of the water recourses, and better economical results. Good control of the system can also help discovering more or less critical errors, like rock-slides in the tunnel, and can by this help avoiding accidents.

Chapter 2

Dynamic modeling

2.1 Control engineering

In order to control and regulate flow systems some theory of control engineering and modeling is investigated. The conditions in a dynamic system changes with time. A condition or state variable can for instance be pressure or flow, and set of measurements of the states is expressed as state vectors. When modeling flow systems the dynamics of the systems must be investigated.

There are two different ways to govern a dynamic system. The first is a feed-forward system, also called program control. This is used when the disturbance is known, and the control signal needed to get the system to the desired operating point can be calculated. The second way is the feedback system. This system measures the parameter, calculates the control signal, and sends this information to a regulator. A dynamic system will have inertia, and will oscillate towards the desired operating point when being treated with more or less load. The two different governing techniques can be combined for an even better system. The feed forward system is the rapid, but inaccurate correction, while the feedback system will do the fine adjustments to the correct value.

For dynamic processes the regulating response can take various forms depending on the system. It is also possible to manipulate the response of the system by using different amplifier values. To regulate a dynamic process the process is modeled by the use of mathematic equations. A good response is only achievable when there is good knowledge of the system, therefore the mathematical model must be accurate. The most central tool in modeling is the use of differential equations.

2.2 Kalman filter

The Kalman filter is one of the most important technologies in modern control engineering, but the use is the hydro power industry is limited. Here some basic theory on how the filter works is presented, and some examples of its implementation. The derivation of the linear equations is presented along with how the nonlinear filter works.

The Kalman filter is a model based state estimator of a stochastic system. The filter bases the estimations on a mathematical model. The model should be accurate, the better the model is, the better the estimation will be. It is still important to consider the performance to the complexity so the system is not too complicated when it is not required.

A Kalman filter algorithm uses a mathematical model to calculate the optimal values of the estimations. Only stochastic models can be used, that is, models that are random and non-deterministic, and can only be described statistically. The Kalman filter can be implemented on both linear and nonlinear systems. For the nonlinear system is called *extended Kalman filter*.

The Kalman filter has numerous applications in the water power industry. If the redundancy of the system is high, the filter can be used to detect measurement error, losses and find malfunctioning sensors. The measurement for pressure loss can for instance be used to find the flow in the plant, which can be hard to measure using traditional methods. The filter can even be used for calibration of flow meters in the plant, if the observability and redundancy is high.

The Kalman filter works by stating equations for the measurements vector, calculates the estimated values for the measurements and compares them to the actual values. The prediction error will then indicate a correction to the states in order to make the calculated measurement values more equal to the actual ones. The filter has good implementation with real time systems, the only values needed are the measurements value and the previous states. This implies that the method does not require large data storage, and does not need to handle large amounts of data at every calculation. Despite of this the filter require a lot of computer capacity because of the heavy calculations.

A linear system can be described by the following equations:

$$x_{k+1} = Ax_k + Bu_k + Gw_k \tag{2.1}$$
$$y_k = Cx_k + Hv_k \tag{2.2}$$

and on general form:

$$x_{k+1} = f(x_k, u_k) + Gw_k \tag{2.3}$$
$$y_k = g(x_k, u_k) + Hv_k \tag{2.4}$$

The different variables are explained in table 2.3 The estimator for the linear system will be:

$$\bar{x}_{k+1} = A\bar{x}_k + Bu_k + K(y_k - \bar{y}_k) \tag{2.5}$$
$$\bar{y}_k = C\bar{x}_k \tag{2.6}$$

Where u is the control vector and y are measurements from the real system. K is the amplification matrix that makes the error as small as possible. A sketch of the Kalman filter principle can be seen in figure 2.1. As shown, the Kalman filter has a model that runs simultaneously as the real process. The z^{-1} in the figure is a symbol of a discrete integrator. z is the discrete version of the Laplace transform s.

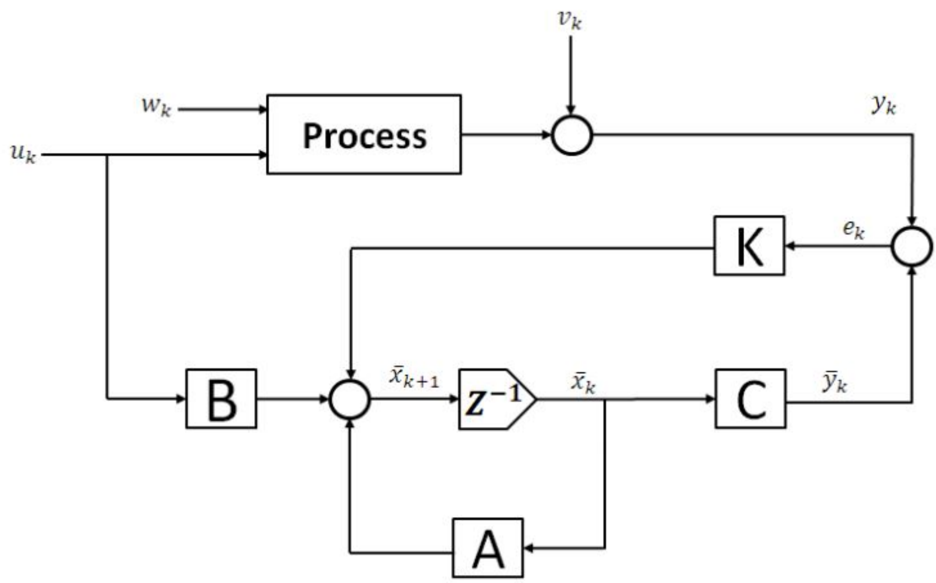

Figure 2.1: Sketch of the Kalman filter principle [3]

x	State vector with n states	$x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x^n \end{bmatrix}$
u	Control vector with m values	$u = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u^m \end{bmatrix}$
y	Measurement vector with r measurements	$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y^r \end{bmatrix}$
w	White process noise vector with n states	$w = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w^n \end{bmatrix}$
v	White measurement noise vector with r states	$v = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v^r \end{bmatrix}$
A	State matrix	n × n
B	Control matrix	n × m
G	Process noise matrix	Normally G = I.
C	Measurement matrix	r × n
D	Control matrix working directly on the measurements	Normally $D = [0]$
H	Measurement noise matrix	Normally $H = 0$

Table 2.1: Explanation of the variables in the Kalman filter [3]

2.2.1 Examples of applications

The regulation of a water tank is to be improved, as shown in figure 2.2[3]. The level h is measured, and a normal PID regulator is used for the regulation. In the bottom of the tank there is a pipe where water is running out. This flow is not measured, and the tank uses a feedback system to regulate the level h. In order to improve the system, a feed-forward system is installed, and we use the Kalman filter to predict the flow F_{out} . The mathematical model of the system will be.

$$A\dot{h} = K_p u - F_{out}$$

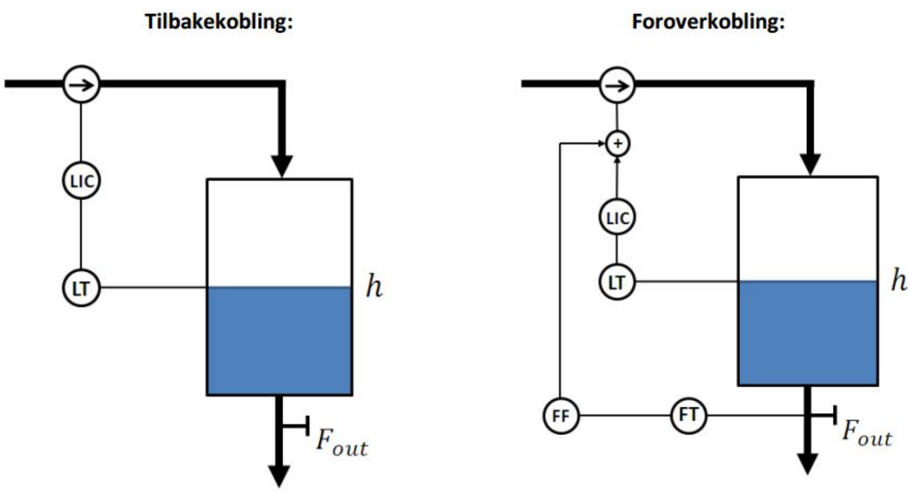

Figure 2.2: A tank with water level h [3]

And the state matrices will become:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & -10 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0.02 \\ 0 \end{bmatrix} u$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix} u$$

From this F_{out} can be estimated in every time step, and the feed forward system corrects the flow in.

The Kalman filter can also be used for dynamic positioning. For instance by the use of an GPS. The signals will be updated in a certain time interval, and does not show the position in between the updates. In this case one can use the Kalman filter to predict the position between the updates. A model alone would probably give a good estimate in the beginning of the simulation, but small errors would escalate. By the use of the Kalman filter the measurement values can "pull" the estimates back on track.

2.2.2 Apriori and Aposteriori

There are two different types of Kalman algorithms. The difference is how they handle the estimates:

- $\bar{x}$ = Apriori estimate, calculated before the current measurements are taken. Also called *time update*.
- $\hat{x}$ = Apoteriori estimate, calculated after the current measurement. Also called *measurement update*.

The predictor type of Kalman filter does not distinguish the apriori and aposteriori estimate, this will give a time-delay. The predictor-corrector type does distinguish, and this is the most common type used today.

2.2.3 Derivation of the equations- Kalman Gain

For the linear equations

$$x_{k+1} = Ax_k + Bu_k + Gw_k \tag{2.7}$$

$$y_k = Cx_k + Du_k + Hv_k \tag{2.8}$$

Where the estimators are:

$$\bar{x}_{k+1} = A\bar{x}_k + Bu_k + K(y_k - \bar{y_k}) \tag{2.9}$$

$$\bar{y}_k = C\bar{x_k} + Du_k \tag{2.10}$$

Where K is the Kalman, used for updating the estimations.

The error between the measurement and the process is:

$$e_k = x_k - \bar{x}_k \tag{2.11}$$

We insert the equations for x_k and $\bar{x}_k$, and then for y_k and $\bar{y}_k$.

$$\begin{aligned}
e_{k+1} &= x_k - \bar{x}_{k+1} = Ax_k + Bu_k + Gw_k - [A\bar{x}_k + Bu_k + K(y_k - \bar{y_k})] \\
&= Ax_k + Bu_k + Gw_k - [A\bar{x}_k + Bu_k + K(Cx_k + Du_k + Hv_k - (C\bar{x}_k + Du_k))] \\
&= Ax_k + Gw_k - A\bar{x}_k - K(Cx_k + Hv_k + C\bar{x}_k) \\
&= Ax_k + Gw_k - A\bar{x}_k KCx_k - KHv_k - KC\bar{x}_k \\
&= A(x_k - \bar{x}_k) - KC(x_k\bar{x}_k) + Gw_k - KHv_k \\
&\text{We insert the error} \\
&= Ae_k - KCe_k + Gw_k - KHv_k
\end{aligned}$$

$$e_{k+1} = (A - KC)e_k + Gw_k - KHv_k \tag{2.12}$$

This is the equation for the error. The Kalman filter algorithm will find the smallest variance of the error estimate.
We define the covariance matrix

$$P_k = E[e_k e_k^T] \tag{2.13}$$

$$and \tag{2.14}$$

$$P_{k+1} = E[e_{k+1} e_{k+1}^T] \tag{2.15}$$

The autocovariance will predict how large the error in the system will be.
We insert (2.12) into (2.15) .

$$P_{k+1} = (A - KC)E[e_k e_k^T](A - KC)^T + GE[w_k w_k^T]G^T - KHE[v_k v_k^T]KH^T$$

and insert the matrices

$$Q = [w_k w_k^T] = \text{auto-covariance matrix to process noise}$$
$$R = [v_k v_k^T] = \text{auto-covariance matrix to measurement noise}$$

to the covariance matrix, and get:

$$P_{k+1} = (A - KC)P_k(A - KC)^T + GQG^T - KHR(KH)^T \tag{2.16}$$

Then, the optimal K is found. The optimal K is the K that makes the error smallest possible. We derivate P_k with relation to K, and set it equal to 0.

$$\frac{\partial P_k}{\partial K_k} = 0 \tag{2.17}$$

We use matrix derivation and end up with the optimal K:

$$K_k = AP_kC^T[CP_kC^T + R]^{-1} \tag{2.18}$$

If we then put the equation for K into equation (2.16), we get:

$$P_{k+1} = AP_kA^T + GQG^T + AP_kC^T[CP_kC^T + R]^{-1}CP_kA^T \tag{2.19}$$

This equation must be solved in every time-step to find the optimal K for the current step. The equation is called the *Ricatti equation* [3].

These derivations are done for the linear case. The nonlinear, extended Kalman filter will find a linearizion of the equations around the current estimate, and is from this able to implement the algorithm.

2.2.4 Q, R and K

Q and R are the Kalman filters tuning parameters. Q is the auto covariance matrix to the process noise w, and R for the measurement noise v. The larger the Q the larger the Kalman gain K, and the stronger the estimate update. A large Q will however imply more noise, and so the two effects must be balanced. If the measurement noise is very large, the K will be very small. This implies that the filter will nearly not use the current measurement when calculating new estimates. The R and Q matrices give a statistic description of how the noise in the system works[9].

The Kalman gain is the parameter that updates the estimates. If K was set to be 0.5, the Kalman filter would simply be an averaging, so the filters job is to find a more clever K to improve the estimates [4]. If the apriori error is small, K is correspondingly small, and therefore the correction is also small. This implies that the previous estimate will be weighted more than the measurements estimating the next value. If the apriori error is large on the other hand, the measurement noise is unimportant, and the K will be large. This effect weighs the current measurements more than the previous state [9].

2.2.5 Example of calculations

A sensor gives a voltage reading, a. The sensor measure a constant physical property, but the measurement will be noisy, so the volt signal will vary a bit above and below a. The standard deviation of the noise is 0.1 volts. The model will look like this [4]:

$$x_k = Ax_{k-1} + Bu_k + w_k$$
$$z_k = Hx_k + v_k$$

- The model is 1 dimensional, so the matrices will be reduced to numerical values.
- A will be 1 as the signal is a constant value.
- We have no control signal, so u_k is zero.
- The value H is also 1. We know that the measurement is the measured value plus some noise. H is normally 1.

The equations reduces to:

$$x_k = x_{k-1} + w_k$$
$$z_k = x_k + v_k$$

The measurements are presented in table 2.2.

The iterations start at k=0, and initial states must be assumed. For

Time	1	2	3	4	5	6	7	8	9	10
Value [v]	0.39	0.5	0.48	0.29	0.25	0.32	0.34	0.48	0.41	0.45

Table 2.2: Measurements [4]

simplicity we set x_0=0 and P_0=1. P must be nonzero, if not, there will not be any gain.

The calculation of the two first iterations are shown, the rest follow the same pattern.

k	1	2
Z_k	0.39	0.5
$\hat{x}_{k-1}$	0	0.355
P_{k-1}	1	0.091
Time update	$\hat{x}_{k-1} = 0$ $P_{k-1} = 1$	$\hat{x}_{k-1} = 0.355$ $P_{k-1} = 0.091$
Measurement update	$K_k = \frac{1}{1+0.1} = 0.909$ $\hat{x}_k = 0 + 0.909(0.390 - 0)$ $= 0.35544$ $P_k = (1 - 0.909) * 1 = 0.091$	$K_k = \frac{0.091}{0.091+0.1} = 0.476$ $\hat{x}_k = 0.355 + 0.476(0.5 - 0.355)$ $= 0.4244$ $P_k = (1 - 0.0.476) * 0.091 = 0.0486$
$\hat{x}_k$	0.355	0.424
P_k	0.091	0.048

The signs of convergence in visible in figure 2.3.

k	3	4	5	6	7	8	9	10
Z_k	0.48	0.29	0.25	0.32	0.34	0.48	0.41	0.45
$\hat{x}_{k-1}$	0.424	0.442	0.405	0.375	0.365	0.362	0.377	0.38
P_{k-1}	0.048	0.032	0.024	0.02	0.016	0.014	0.012	0.011
Time update								
Measurement update								
$\hat{x}_k$	0.0442	0.405	0.375	0.365	0.362	0.377	0.38	0.387
P_k	0.032	0.024	0.020	0.016	0.014	0.012	0.011	0.010

Table 2.3: Iteration results [4]

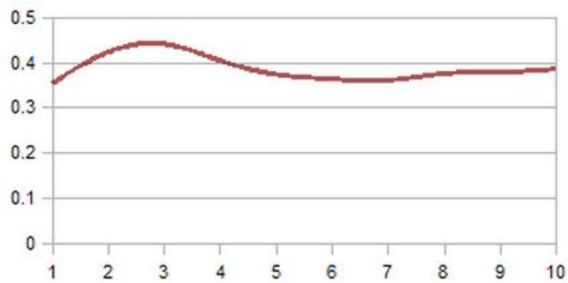

Figure 2.3: The kalman filer converges to the real over a few iterations. [4]

2.2.6 Observability

To implement the Kalman filter the system must be observable. For the following system:

$$x_{k+1} = Ax_k + Bu_k$$
$$y_k = Cx_k + Du_k$$

The observability matrix is defined

$$O = \begin{bmatrix} C \\ CA \\ \vdots \\ CA^{n-1} \end{bmatrix} \tag{2.20}$$

The system is observable if the range of the system is equal to n, or the determinant of O is not equal to 0.

The Kalman filter can only be implemented in a observable system. The systems initial conditions $x(t_0)$ must be possible to find from y(t) over a final time interval. For instance, if measuring the speed of a car, without any information of the position, the system is not observable if the information on both the speed and position are required. If the position had been measured, the speed could have been found by derivation. The system is observable because the speed influences the position, and therefore also the measured values. [3].

2.3 Modeling equations and losses

The loss equations has been used to predict some of the variables in the Kalman model. The original plan was also to calculate the loss in different parts of the rig, and compare this to both the measured values and the Kalman filter values to see how well the Kalman filter operates. The loss equations has been implemented into labVIEW subVIs, but because of the late change of the RIO, many of the sensors signals were not logged and the use of the subVIs reduced. They have therefore not been implemented in the main Kalman filter program.

A general loss formula is on the form:

$$\Delta h = KQ^2 \tag{2.21}$$

A graphical representation of equation (2.21) is shown in figure 2.4

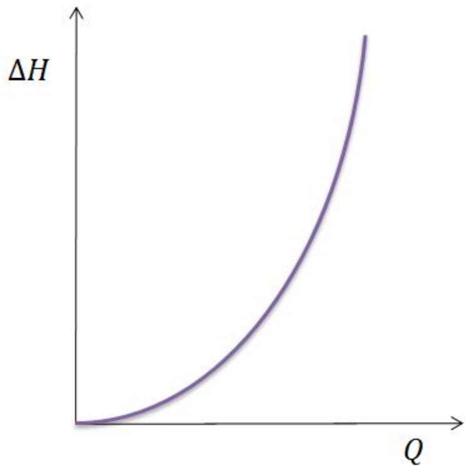

Figure 2.4: The relation between ΔH and Q

2.3.1 Bernoulli

The Bernoulli equation states that if a fluids velocity is increased, the pressure will drop, and visa versa. Bernoulli is applicable on incompressible flow moving at low Mach numbers. The equation is for frictionless flow, but a loss segment can be added.

$$\frac{1}{2}\rho v^2 + \rho g h + p = constant \tag{2.22}$$

2.3.2 Reynolds number

The Reynolds number describes how the flow behaves. The conditions changes throughout the rig and with different operating points. The flow in pipes are said to be laminar when the Reynolds number is below 2300, above this there is a transition phase before the flow is fully turbulent at Reynolds equal to approximately 10^6 [14]. The flow in the swirl-rig is considered turbulent at all times, even though there might be cases where the flow is in transition phase. Several of the parameters in the Reynolds equations are temperature dependent. From White [14] there are some curve fits that finds the correct values for different temperatures.

$$Re = \frac{\rho U D_H}{\mu} = \frac{\rho Q D_H}{A\mu} \tag{2.23}$$

$$\rho \approx 1000 - 0.00178 \mid T - 4 \mid^{1.7} \tag{2.24}$$

$$ln\frac{\mu}{\mu_0} \approx -1.704 - 5.306z + 7.003z^2 \tag{2.25}$$

where

$$z = \frac{273K}{TK}$$

$$\mu_0 = 0.001788\frac{Kg}{ms}$$

In order to get the correct Reynolds number, the rig has been parted into Reynold-zones to simplify the calculations.

2.3.3 Major losses in pipes

Turbulent flow are strongly affected by roughness in the pipe wall, and the loss created from this is what we call Major losses in piping systems. The most used way to find the friction in pipes is by use of the Moody diagram, based on the formula :

$$\frac{1}{f^{\frac{1}{2}}} = -2.0log\left(\frac{\frac{\epsilon}{d}}{3.7} + \frac{2.51}{Re_d f^{\frac{1}{2}}}\right) \tag{2.26}$$

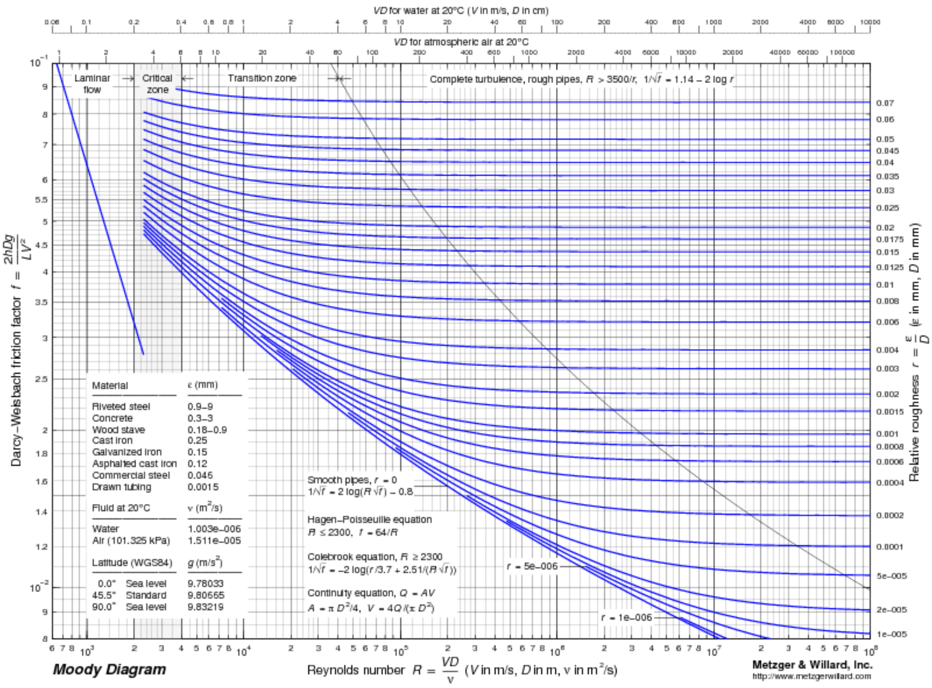

Figure 2.5: The Moody Diagram [5]

The Moody diagram is shown in figure 2.5.

There is an alternative equation, developed by Haaland, which is easier to solve.

$$\frac{1}{f^{\frac{1}{2}}} = -1.8log\left[\frac{6.9}{Re_d} + \left(\frac{\frac{\epsilon}{d}}{3.7}\right)^{1.11}\right] \tag{2.27}$$

This equation varies less than 2 percent from (2.26)[14].

The relation between f and head loss is

$$h_f = f\frac{LV^2}{d2g} \tag{2.28}$$

2.3.4 Pipes in series

To calculate losses in pipes in series some basic continuity rules apply. The flow rate will be the same in all the pipes, and the head loss in the system will be the separate head losses added up.

$$Q_1 = Q_2 = Q_3 = \text{constant} \tag{2.29}$$

$$V_1 d_1^2 = V_2 d_2^2 = V_3 d_3^2 \tag{2.30}$$

$$\Delta h_{A \to B} = \Delta h_1 + \Delta h_2 + \Delta h_3 \tag{2.31}$$

2.3.5 Pipes in parallel

For pipes in parallel the pressure drop in each pipe will be the same as in the others, and continuity states that the total flow is the sum of all the flows.

$$\Delta h_{A \to B} = \Delta h_1 = \Delta h_2 = \Delta h_3 \tag{2.32}$$

$$Q = Q_1 + Q_2 + Q_3 \tag{2.33}$$

2.3.6 Pipe network

Piping networks can be quite complex, and cumbersome to calculate, but they follow the same basic rules:

- The net flow in any junction must be zero
- The net pressure around any closed loop must be zero.
- All pressure changes must satisfy the Moody losses and the minor losses.

By using these rules for every junction and independent loop in the system, a set of equations. Solutions may be found by numerical iteration.

2.3.7 Minor losses

For any pipe system there will be minor losses in addition to the friction losses. The minor losses can be parted into these types:

- Pipe entrance or exit.
- Sudden expansion and contraction.
- Bends, elbows, tees and other fittings.
- Valves, open or partially closed.
- Gradual expansion or contraction.

In the swirl rig there will be both bends, valves, t-bends, contraction and expansion. Even though the name of the losses is *minor*, the losses are not necessarily that small. In the case of an partially closed valve, the loss coefficient can reach very high values, and add on large losses to the system.

2.3.8 Bends

A bent curve in a pipe will always induce more loss than a straight pipe. The bend creates low separation of the curved walls and creates a swirl because of the centripetal acceleration. For a 90 degree bend the curve fit formula for the loss is:

$$K \approx 0.338\alpha \left(\frac{R}{d}\right)^{0.84} Re_D^{-0.17} \tag{2.34}$$

$$\alpha = 0.95 + 4.42 \left(\frac{R}{d}\right)^{-1.96} \geq 1 \tag{2.35}$$

Where R is the radius of the bend in center of pipe, and d is the diameter of the pipe.

2.3.9 Losses in valves

The swirl rig contains 4 gate valves of which 1 can be controlled electronically. The remaining three are manually operated. There are one valve on every pipe section. The losses in the valves are very dependent of the opening, and the losses become large when the valve are almost closed. From [10] we have these formulas for the losses:

$$K = exp(2.3\sum_{i=0}^{6} a_i \left(\frac{h}{D_0}\right)^i \tag{2.36}$$

for

$$0.2 \leq \left(\frac{h}{D}\right) < 0.9$$

Where

$$a_0 = 7.661175$$
$$a_1 = -72.63827$$
$$a_2 = 345.7625$$
$$a_3 = -897.8331$$
$$a_4 = 1275.939$$
$$a_5 = 938.8331$$
$$a_6 = 28.8193$$

and

$$K = 0.6 - 0.6\left(\frac{h}{D_0}\right) \tag{2.37}$$

for

$$\left(\frac{h}{D_0}\right) \geq 0.9$$

D is the pipe diameter, and h is the opening height of the valve.

2.3.10 Losses in T-bends

Losses in a T-bend is different for which direction the flow travel and what section that is of interest. For t-bends where flow is leaving the main pipe, the losses in the main pipe can be described as follows [10]:

$$K_{st} = \frac{\Delta P}{\rho\frac{V^2}{2}} \tag{2.38}$$

$$K_{st} = \frac{\zeta_{c,st}}{\left(1 - \frac{Q_s}{Q_c}\right)^2 \left(\frac{F_c}{F_{st}}\right)^2} \tag{2.39}$$

And the losses in the side branch as follows:

$$K_c = \frac{\zeta_{c,s}}{\left(\frac{Q_s F_c}{Q_c F_s}\right)^2} \tag{2.40}$$

$\zeta_{c,s}$ and $\zeta_{c,st}$ is found by the use of tables in [10].
For flows where the branch is going into the main pipe the losses for the main pipe is the following:

$$K = 1.55\frac{Q_{branch}}{Q_{tot}} - \left(\frac{Q_{branch}}{Q_{tot}}\right)^2 \tag{2.41}$$

Chapter 3

The Test Rig and Equipment

The experiment was conducted at the Water power lab at NTNU in Trondheim. The existing Swirl rig on the 2. floor was used.

3.1 The rig

The rig is originally made to simulate the swirl that may occur in the draft tube of a Francis turbine when operating off best efficiency point. A schematic drawing of the rig is shown in figure 3.6.

The flow is pumped from a reservoir and through a flowmeter. Three throttling valves allows distribution flow into three different pipes: the main pipe, the swirl generator pipe and the nozzle pipe. A valve is shown in figure 3.1. The swirl generator flow will meet the main pipe in the so called swirl generator, and will increase the swirl and create a fluctuating vortex downstream of the joint, whereas the nozzle flow will inject water contrary to the swirl flow, and therefore suppresses the the formation of the fluctuating vortex. The flow continues through a observation section made of plexiglas and through a back pressure valve. The back pressure valve enables the possibility to build pressure in the rig. The plexiglas section is made for observations and to to optic measurements. This will not be performed in this thesis.

On several locations on the rig there are pressure outlets. The pressure outlets are simply holes in the pipe wall, with nipples and threads to fasten the pressure sensors. The holes are polished on the inside not to disturb the flow too much.
The main pipe has an inner diameter of 150mm, the first part of the swirl generator pipe is 100mm, then the area is reduced to 50mm before entering the swirl generator . The nozzle pipe has a diameter of 50 mm, and ends up in a nozzle where the diameter is 10mm.

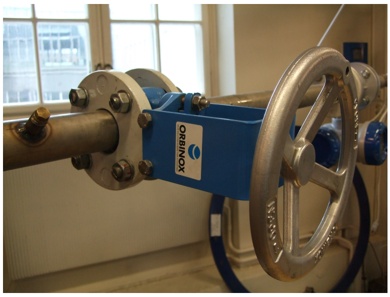

Figure 3.1: Valve

3.1.1 Modifications

The rig had to be modified for it to satisfy the test carried out in this thesis. More pressure measurement point had to be welded, and the main exit valve had to be changed; a control system was added so that the opening was controllable and measurable directly from the 2.floor.

3.1.2 Calibration

The sensors must be calibrated to find the relations between the amplitude signals and the real values. The sensors gives values from 4 to 20 mA. This implies that that when the pressure in the system is zero, the signal will show 4mA. This will help discovering errors, as it it is possible to distinguish between no pressure and no/wrong signal.

The single board RIO input requires values from -10 to 10 Volt. The signals are therefore transferred to Voltage signals by adding a resistance of 500 ohm, and use Ohms law.

$$U = R \times I$$
$$0,5k \times 4mA = 2V$$
$$0,5k \times 10mA = 10V$$

$$4 - 20mA \Rightarrow 2 - 10V$$

The Compact RIO can log both V and mA, by using the equivalent modules. Because the logging was supposed to be done through the cRIO, all the sensors are calibrated in Ampere through the cRIO. Because the late change to the SbRIO, the calibration constant were recalculated to fit to voltage signals instead. The transformation from ampere to volt is done by a high precision resistance.

The calibration is carried out in a self-produced calibration program. The senors are connected through the RIO, as they will be during the experiment, to make sure that the measurements for calibration and experiment is done the same way. The LabVIEW calibration-program is presented in chapter 4.

3.2 Flowmeters

There are flow-meters placed on 4 different location on the rig. This allows the user a good overview of the flow in the different pipes. The flow meters are electromagnetic of the type Krohne, OPTIFLUX 2300C, and 2000F. The measuring principle follows Faradays law; A electrically conductive fluid flows inside the flow meter. Inside the flowmeter there is a magnetic field generated by a current induced by a flow through a pair of coils. A voltage is generated, and picked up by electrodes. This voltage is proportional to the flow velocity, or Q, since the inner diameter of the flow meter is known [11]. The principle is shown in figure 3.2, and one of the flow-meters on the rig are shown in figure 3.3.

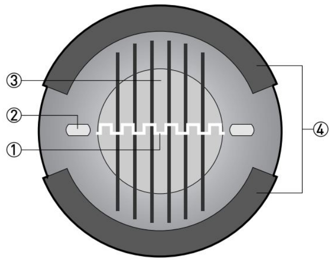

Figure 3.2: Flow meter principle [11]

3.2.1 Calibration

There are 3 flowmeters that needs to be calibrated. The main flowmeter will be calibrated to the calibration tank, and the two others will be calibrated towards that. The main flowmeter is calibrated with voltage signals.

The calibration tank has a computer controlled tilting valve. This will, for a set amount of time, direct water into the tank. The valve has very good time precision. The water in the tank is weighed by the use of calibrated weights. The flow is calculated based on the weight, the filling time, and other parameters like temperature and pressure. The calibration is a time consuming process since a certain amount of water is needed to get the uncertainties on an acceptable level. To do the calibration alone can be cumbersome, and to get someone to help is recommended. One person can control the calibration tank, and one can do the logging in the control room. A small calibration procedure will be given in appendix A. The results from the calibration process is shown in table 3.2.1, and the calibration rapport is in appendix B.

The two remaining flowmeters will be calibrated towards the first. This process is easier than using the calibration tank, but will imply somewhat higher uncertainties. The calibration is conducted by running the rig at

Figure 3.3: Flow meter

Type	Serial number	a	b	Error
Optiflux 2000 F	A05 1090	0.012345462	-0.025160210	- %
Optiflux 2300 C	A07 00871	6.187273	-0.025382	0.189443 %
Optiflux 2300C	A07 00945	3.107779	-0.013078	1.372417 %

Table 3.1: Calibration results for flow meters

different operating points. When the mean signals from the two flowmeters are stable, a calibration point is logged. This is done for the whole range of operating points. An important thing to notice is that calibrating in the lower flow range might not work , because when running the pump on a too low rpm, the flow will disappear completely because of the elevation of the rig in relation to the pump.

3.3 Pressure transmitters

To measure the pressure in the rig both pressure transmitters of the type Druck PTX 610 and differential-pressure transmitters of the type Fuji FCX, is used. The absolute pressure transmitters are placed tangentially to the flow direction, and will measure the static pressure. They measure the pressure by use of a silicon pressure sensor that is restrained in a high integrity glass metal seal, so that there is both electrical and physical isolation from the pressure media. An diaphragm of hastelloy transmits the pressure to the sensor via a silicone oil filling. Figure 3.5 shows the inside of a PTX pressure transmitter [8]. The pressure transmitters can measure 2.5 bar abs. The absolute pressure sensors is used because the environment inside the rig may go below atmospheric.

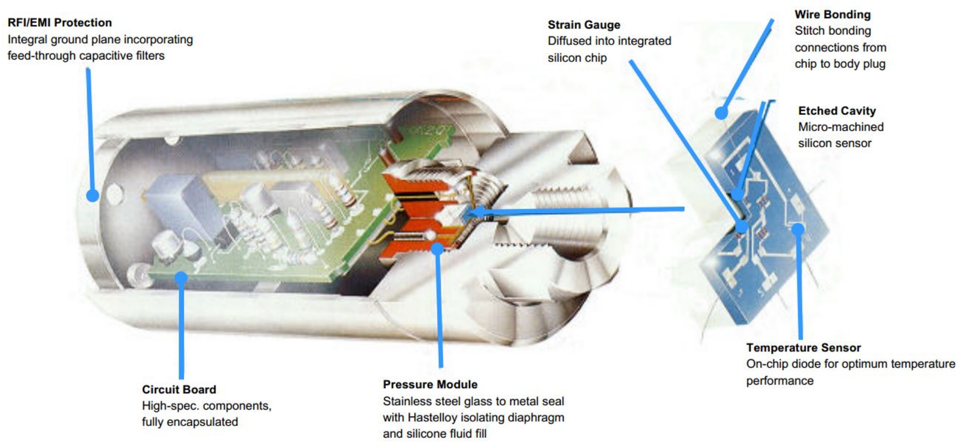

Figure 3.4: The inside of a PTX pressure transmitter [1]

The differential pressure transducers measure the difference in pressure of two locations. Because of this the pressure sensors work independently of the atmospheric pressure. The inside of such a sensor is seen in figure 3.5. The sensors are attached by small plastic hoses to the rig.

The pressure transducers will be placed as shown in figure 3.6. Normal pressure transducers marked with red numbers and differential pressure as red Dps.

The overview of which sensors is where it found in table 3.2.
The picture 3.7 shows 4 different pressure outlets, where one of them is attached to a hose.

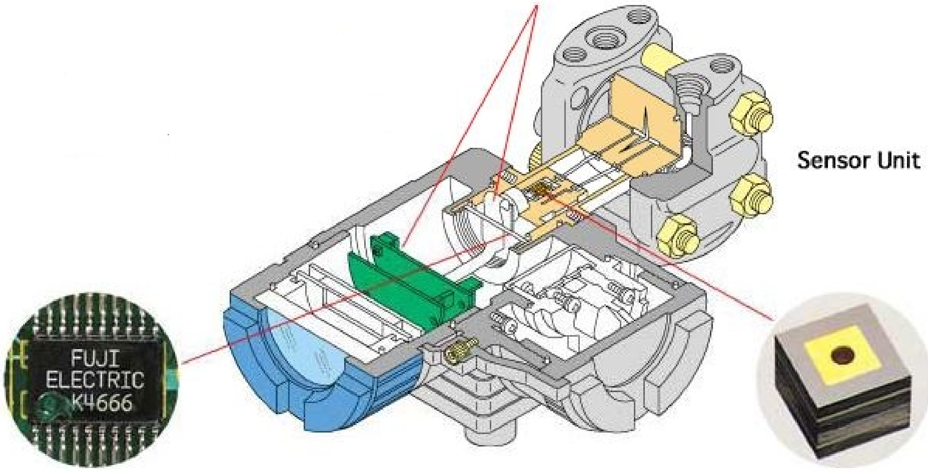

Figure 3.5: The inside of a Fuji differential pressure transmitter [8]

3.3.1 Calibration

The pressure transmitter will deliver a certain signal for every pressure. The calibration will be done by the use of a dead weight calibrator of the type P3023-6-P from GE Sensing. The pressure transmitter is coupled to a pressure chamber. The pressure is controlled by the use of a piston and additional weights with an equivalent pressure. These weights have been calibrated for international standard gravitation, so the pressure should be corrected for local gravitation.

$$p_{local} = \frac{g_{local}}{g_{SI}} \times p_{calibrator}$$

For local g at the Water Power Lab:

$$p_{local} = \frac{982.147}{980.665} \times 1 = 1.0051$$

So all the measured pressures should be multiplied with 1.0051.

The calibrator is shown in figure 3.8. The calibration is done by logging the pressure and the mA signal and do a linear curve fit. The results

Sensors	Type	Location
PTX610 SN 2738456	Absolute pressure	P2
PTX610 SN 2738458	Absolute pressure	P1
PTX610 SN 2480173	Absolute pressure	P3
Fuji FCX A5A5304	Differential pressure	DP1
Fuji FCX AII A5E7992F	Differential pressure	Dp4
Fuji FCX 9602 N 0004 CK1	Differential pressure	Dp2
Optiflux 2000 F SN:A05 1090	Flow	Q1
Optiflux 2300 C SN:A07 00945	Flow	Q3
Optiflux 2300 C SN:A07 00871	Flow	Q4

Table 3.2: Location of sensors

Name	Serial number	a	b	max error %
PTX 610	SN 2480173	156.167608	-0.621796	0.056319
PTX 610	SN 2738456	156.244957	-0.623428	0.094633
PTX 610	SN 2738458	156.237595	-0.624527	0.07392
Fuji FCX	A5A5304F	81.391035	-0.319467	0.162098
Fuji FCX AII	A5E7992F	125.185811	-0.427860	0.318891
Fuji FCX	9602 N 0004 CK1	157.112975	-0.628592	1.145053

Table 3.3: Calibration results for pressure transmitters and the differential pressure transmitters

will give a calibration formula on the form:

$$p = a \times X + b$$

Where a and b are the calibration constants.

The results from the calibration can be found in table 3.3.1. And the calibration rapports in appendix B.

3.4 Uncertainty

There are uncertainties connected to every measurements. To find the total uncertainty, the uncertainties from both the calibrator apparatus and the ones connected to the measurements are added. The measurement error is the difference between the measured value and the correct value. The correct value is not known, and therefore statistical methods for estimates are in order. From this it's possible to find a confidence interval where the actual value will be, with a certain probability. This probability is chosen, the industry normally uses 95 %, and this is also done in this thesis. The uncertainties in the calibration have been programmed into the LabVIEW calibration program. This means that the errors are calculated along the way, and the error can be found even though the operator does not have a good knowledge of uncertainty analysis. Both random error and regression error has been implemented in the program. [13]

3.4.1 Random error

Random error are caused by the small variations in the signal from the sensors, even though the physical values are the same. The measurements deviation from the mean value will behave in a stochastic manner, and therefore it is assumed that the measurements approach a normal distribution when the number of measurements increase. That implies that the error will decrease with the number of measurements. Since we have a finite amount of measurements the normal distribution cannot describe the distribution accurately, and therefore the student-t distribution is used. The confidence interval around the mean is shown in equation (3.1).

$$P\left(\bar{X} - \frac{t \times S}{\sqrt{N}} \leq \mu \geq \bar{X} + \frac{t \times S}{\sqrt{N}}\right) = 1 - \alpha \tag{3.1}$$

$$S = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(X_i - \bar{X})^2} \tag{3.2}$$

$$\begin{aligned}\bar{X} &= \text{Mean value}\\ t &= \text{Student t factor}\\ S &= \text{Standard deviation}\\ N &= \text{Number of samples}\end{aligned}$$

3.4.2 Regression error

When making a linear approximation on the measurements, there will be an error due to the assumption that all the measurements are on the curve. The following equations are needed to calculate the regression error.

$$S_{XX} = \sum_{i=1}^{N}(x_i - \bar{X})^2 \tag{3.3}$$

$$S_{YY} = \sum_{i=1}^{N}(y_i - \bar{Y})^2 \tag{3.4}$$

$$S_{XY} = \sum_{i=1}^{N}(X_i - \bar{X})(y_i - \bar{Y}) \tag{3.5}$$

$$\tag{3.6}$$

S_{XX} is a measure of the error in the x direction, while S_{YY} is in the y-direction. S_{XY} is a measure of the combined error in both x and y direction.

$$SEE = S_{YY} - \frac{S_{XY}^2}{S_{XX}} \tag{3.7}$$

$$s^2 = \frac{SEE}{N-2} \tag{3.8}$$

The confidence interval of the mean response around the regression line is expressed by:

$$\hat{Y} - t \times s\sqrt{\frac{1}{N} + \frac{(X_0 - \bar{X})^2}{S_{XX}}} \leq \mu \geq \hat{Y} + t \times s\sqrt{\frac{1}{N} + \frac{(X_0 - \bar{X})^2}{S_{XX}}} \tag{3.9}$$

$$\hat{Y} = \text{mean response of an input}$$

SEE is the sum of squares of the errors about the regression line, and s^2 is an estimate of the variance of the regression line produced with SEE.

3.4.3 Total error

The total error is found by adding the squared of all the errors and taking the square root of the total.

$$Errors = \pm\sqrt{E^2_{Calibrator} + E^2_{Random} + E^2_{Regression}} \tag{3.10}$$

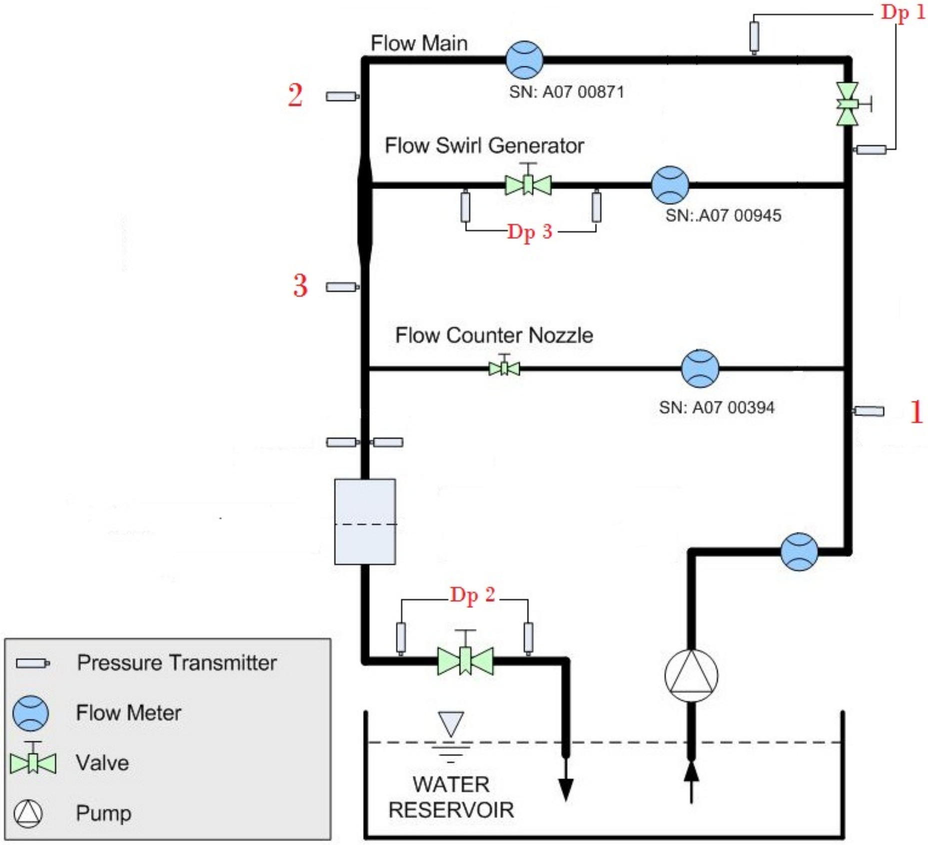

Figure 3.6: Location of sensors on the rig, modified from [2]

Figure 3.7: Pressure outlets on the rig

Figure 3.8: Dead weight calibrator

3.5 Reconfigurable Input/output- RIO

A *reconfigurable Input/Output*, called RIO, is a technology that combines the reconfigurable FPGA, real time and the graphical programming tools in LabVIEW.

There are different types of RIOs, in this thesis a compact RIO (cRIO) and single board RIO is used. The single board RIO has been used for both training and experiments. It has an extra board mounted on top where there are LEDs, temperature sensors, an LCD screen and other applications. This makes the RIO a good beginners board because your results can be visualized. The cRIO was to be used in the main experiments because of its flexibility and many input terminals, but the RIO was relatively old and did not support some of the functions in the program automatically. The single board RIO has 16 analog inputs, but many of them does not have a input terminal and some are used for the LEDS and temperature sensor. In order to use them for the experiment, the board must either be taken apart and the inputs soldered, or fewer sensors must be used. In the end the single board RIO with fewer inputs was used. It was considered not practical to start soldering, and therefore missing the opportunity to use all the training functions on the board.

The sbRIO and the cRIO are configured the same way, and the LabVIEW project will have almost the same configuration. To be able to understand the features of the RIOs, some background information might come in handy, especially when trying to solve issues that will appear along the way.

3.5.1 FPGA

A Field Programmable Gate Array, called an FPGA, is a digital integrated circuit that contain programmable blocks of logic. These blocks can be configured by the user, thereof the name ”Field Programmable”. Some FPGAs can only be programmed once, so called *one-time programmable*(OTP), while others may be programmed over and over. They contain millions of logic gates and can be used to implement very large and complex functions. They come with embedded microprocessor cores and high speed input/output (I/O) interfaces, and this makes it possible to implement almost anything [12].

A FPGA consist of one basic logic cell duplicated thousands of times. The small logic cell is made from one lockup table (LUT), a flip-flop and a 2 to 1 mux (multiplexer) that selects which signal to forward. The Lut is similar to a small RAM that is able to implement any logic function, it has some inputs and a AND gate, and the result from this is OR-ed with another input. Each logic cell can be connected to other cells, and this interconnection makes it possible for the different logic cells to interact to create all the functions of an FPGA. An illustration of the connections are illustrated in figure 3.9 [7].

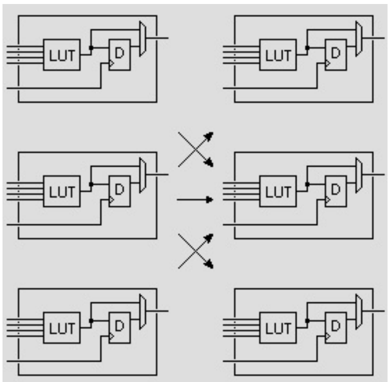

Figure 3.9: Several logic cell connected [7]

3.5.2 Real time

A real time system does not necessarily mean a fast system, it means that it has absolute reliability, that it should meet a certain timing demand. A real time system needs to be in sync with the world. If it falls out, it has failed. Determinism is the term used to decide if a system is able to complete a task in a specified amount of time. The real time system has to be faster than the events coming in. If it is connected to a fighter airplane, it has to be really fast. If it is connected to a glacier, not necessarily that fast.

The real time system does this by having complete control of all the tasks to be executed. A operating system in a computer on the other hand, has background programs, interference by the outside (mouse, keyboard) and can set high priority tasks to wait while executing lower priority tasks. The real time system will prioritize important tasks first, not disturbed by anything else.
A real time system is parted into 2 types, hard and soft real time systems. If a system fails to meet the deadline, but will function despite of this, it is called a soft real time system. If a hard real time system fails the results will be much more severe, like an aircraft crash. [6]

3.5.3 Setup - connection to a PC

Both the Single board RIO and the cRIO is connected to a computer through the ethernet, via a switch. This switch decides how to treat the connected traffic from various ports, based on their knowledge of the network. The computer has one input and one output in the network card, and so does the RIO. Without the switch the computer would have sent information from the output on the computer to the output on the RIO. The switch rearranges this so that the information from the computers output will go to the RIOs input.

When the RIO is properly connected to the computer, it will show as a local network. This network needs to be given a static IP address so that LabVIEW is able to find it. The RIO used in this thesis has the IP address 192.168.0.2, and it given a subnet mask of 255.255.255.0. The subnet mask is a guide to where to find the RIO. The number 255 means that the number has to be the same, in this case 192, 168 and 0 needs to be the same, while the last number can be any number between 0-255. The subnet mask is like a neighborhood, you specify which neighborhood it has to search in, so it does not have to search the entire city of IP addresses. Figure 3.10 shows the IP address settings on the local network. In order to get normal Internet back after finishing the programming. The network must be set to find the IP address automatically.

The Rio board will appear in the NI MAX window (if it does not, the firewall might be the problem). Here you must give the RIO a static IP

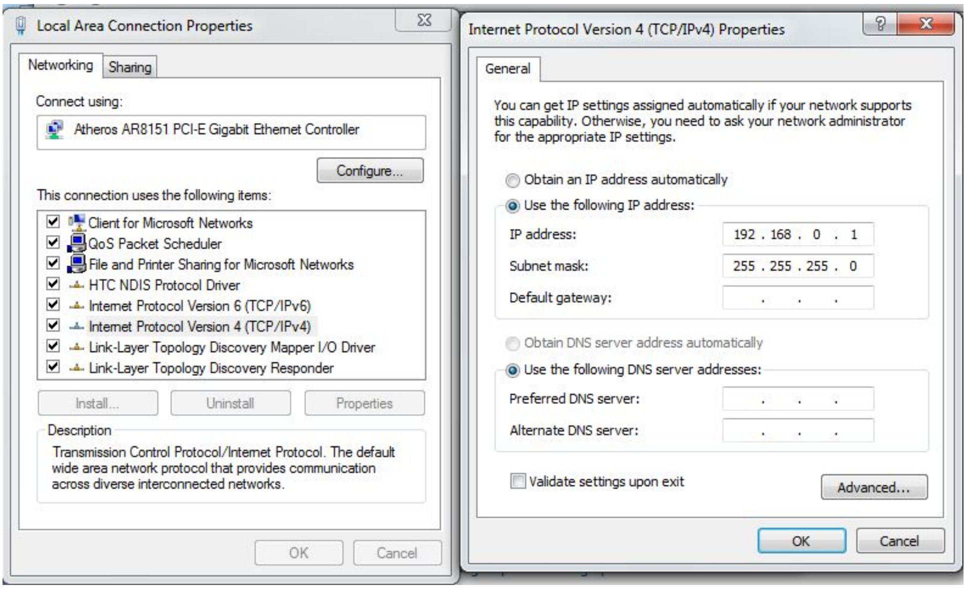

Figure 3.10: The local network settings

adress, this IP will must be set identical to the local network, except from the last number which must different. This way the computer and the RIO is in the same subnet and is able to communicate. Figure 3.11 shows how you set a static IP adress in NI MAX

To check for connection try to ”ping” the RIO. Open the cmd.exe and write ”ping 192.168.0.2” in the commando window. If it replies that all 4 messages were received, is is connected. This method can be very useful for debugging connection issues between the computer and the RIO, which may occur every now and then.

In NI MAX you will have to install software on RIO. This is done by pressing Add/remove software, and install the programs you need. If the RIO is lacking necessary programs it will say so when trying to deploy the program. After the installation the RIO is ready and the programming can commence.

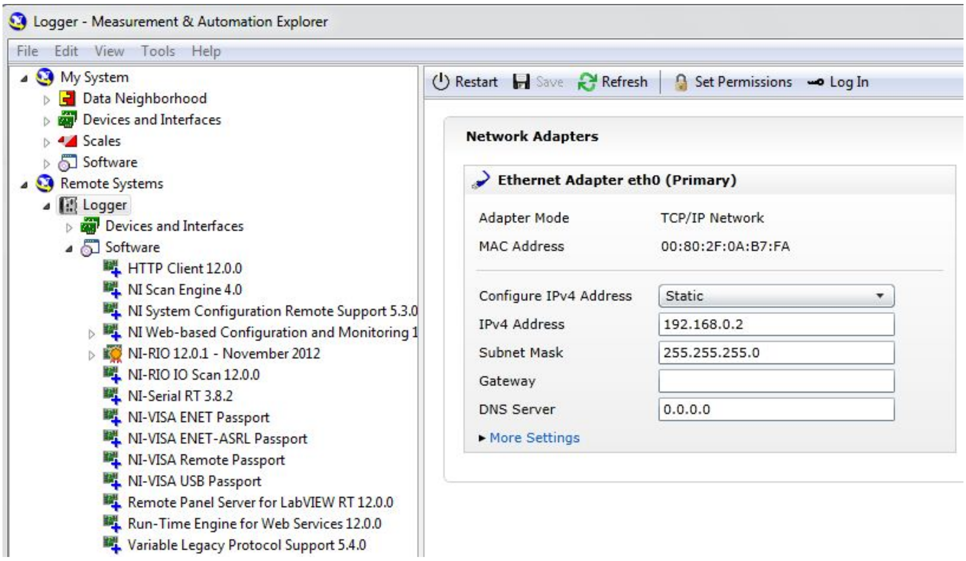

Figure 3.11: How you set the static IP adress in NI MAX

3.5.4 Transfer the program

To transfer the LabVIEW FPGA program to the RIO the compiler system is started. LabVIEW will first make the program into logic functions, and compile it into a bitfile that can be transferred to the FPGA. Then the bitfile gets transferred through the ethernet connection and voila, the FPGA works according to your logic function. The whole process takes about 10-20 minutes, and it can be done as many times as desired. This is great for developing purposes, if the first trial did not work out, it can done again as many times as needed. The real time programs only needs to be deployed, and does not nearly use as much time as the FPGA compiling.

Chapter 4

LabVIEW

4.1 Introduction

LabVIEW is a program used for virtual instrumentation. A LabVIEW program consist of two parts, one logic background, where the programming is located, and a front panel, or user interface, for reading results and operating the program. The user interface is meant for operators both with and without much previous knowledge of LabVIEW.

4.1.1 LabVIEW projects

When programming RIOs a project folder is required to systematize which programs goes where. The RIO, the real time target, and any logging modules must be added to the project. The real time VIs must be placed on the real time target, the FPGA VIs on thee FPGA, and so on. The project folder will also contain any subVIs and shared variables used in the project. It is a handy way to keep an overview of all the elements in the project.

4.2 Calibration program

In order to calibrate all the sensors used in the experiment, a calibration program is required. The best results are obtained if the calibration is performed through the same connections as used in the experiment. The program is made by help from Håkon H. Franckes calibration program.

The pressure sensor calibration requires input on pressure and uncertainty variables. The flow calibration uses signals and calibration constants from the main flowmeter to calculate the correct flow. As the program requires user input, it also requires a user interface. In addition, the functions needed to generate rapports were not available on the real time or FPGA platform, hence the calibrator program is located in a VI that runs on the host computer. The calibration program used for the pressure sensor calibration will be the one presented. The calibration program for the flowmeter is identical except from the pressure input, which has been swapped with the calibrated signal from the main flowmeter.

The FPGA and RT programs are simple. Their purpose is to send values through to the computer, and has no user interface. The RT program is required to run simultaneously as the host program, in order to transfer the measured values.

4.2.1 Host program

The host program is where the actual calibration takes place. First the ampere value from the real time program is read through the shared variable function. The refnum is connected to a read value function inside the while loop. Outside the loop the connection to the variable is closed. The ampere value is then transformed to an array, and the mean is calculated. The array is made by the use of a shift register and a build array function. This way the array will add the latest ampere value to the end of the array for every while-loop iteration. All this shown in figure 4.1.

In order to calculate a new mean for every pressure change, the array of ampere values requires a clear function. This is obtained by the use of a case structure. When the boolean into the structure is false, the array runs straight through, but when the boolean ”clear mean and graphs” is pressed, the structure sends an empty array both to clear the array values, and to clear the history of the array. The graph for the mean is also cleared. Every time the button is pressed the mean will be calculated from scratch. This way the mean is calculated only for the desired values. The

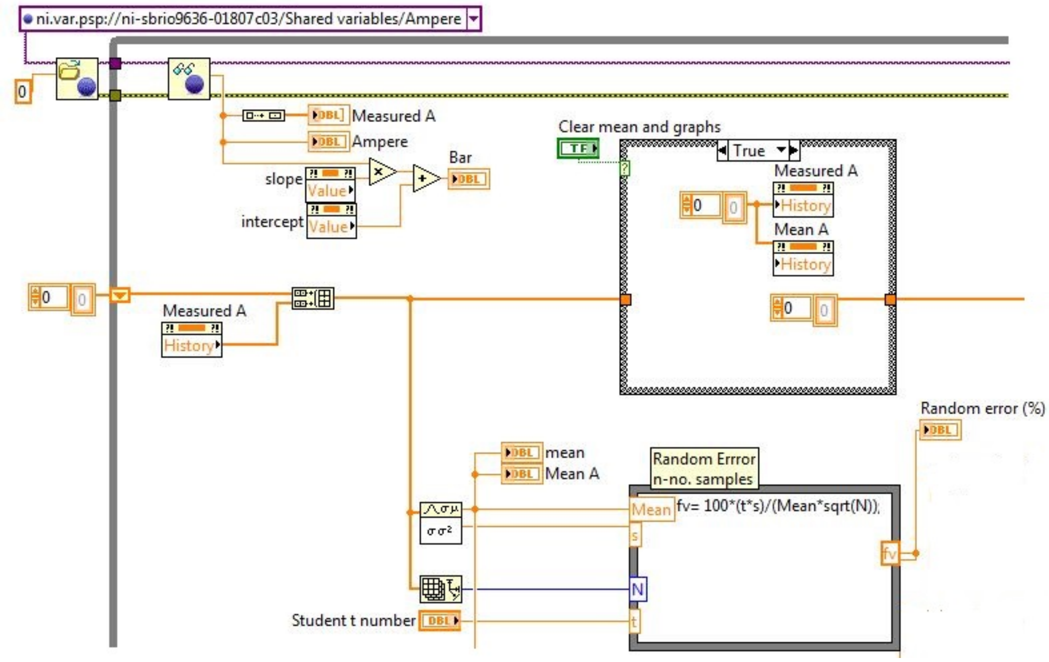

Figure 4.1: The first steps in the calibration program

Clear mean and graphs case structure is shown to the right in figure 4.1.

The mean and random error value is sent to a new case structure where points are logged. When the pressure is correct, the mean value stable and the random error small enough, the ”Log point” boolean button is pressed and the value of the pressure, the mean value and the error is added to their respective arrays. If a point is logged incorrectly it is possible to delete the point by pressing the ”Delete point” boolean, after choosing the correct index of the wrong number. The logging and deleting case structures are shown in figure 4.2. The logged ampere and pressure points are shown in a table in the front panel.

The pressure and ampere arrays are sent to a for-loop where the errors are calculated. The for-loop with its calculations are shown in figure 4.3.

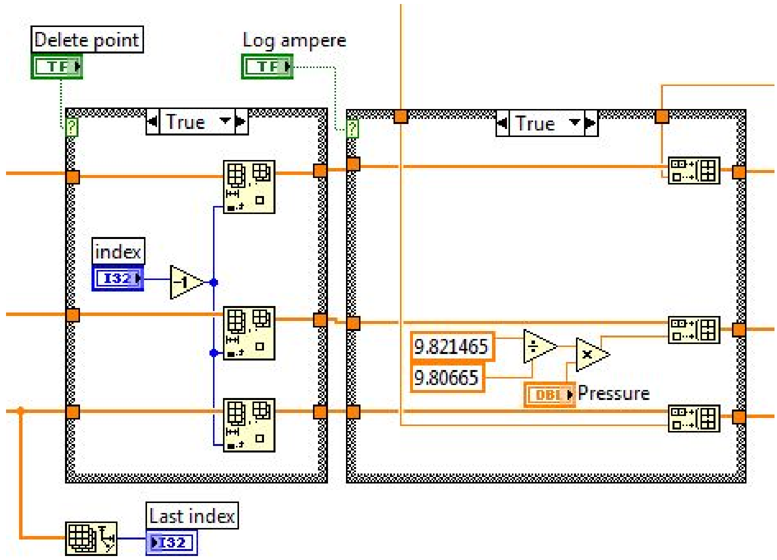

Figure 4.2: Delete and log points

The pressure and the ampere arrays are linearized to find the fitted linear curve for the logged measurements. The fitted pressure values, the pressure raw data and the upper and lower errors are clustered with the ampere values and presented graphically. This graph is used in the report. The raw pressure data, the ampere signal, the fitted pressure data, the deviation between the raw and the fitted pressure data, and the error in both bar and % are gathered in a array of string and saved in the report. The linear fit slope and intercept are converted to the equation written in the report by adding together as a string of the different elements and sends this to the report generator block. All this is shown in figure 4.4.

The report generator is located inside a case structure. The report is generated only when the ”Generate report” boolean is pressed. The headers for the table and the report file location must be set. The report

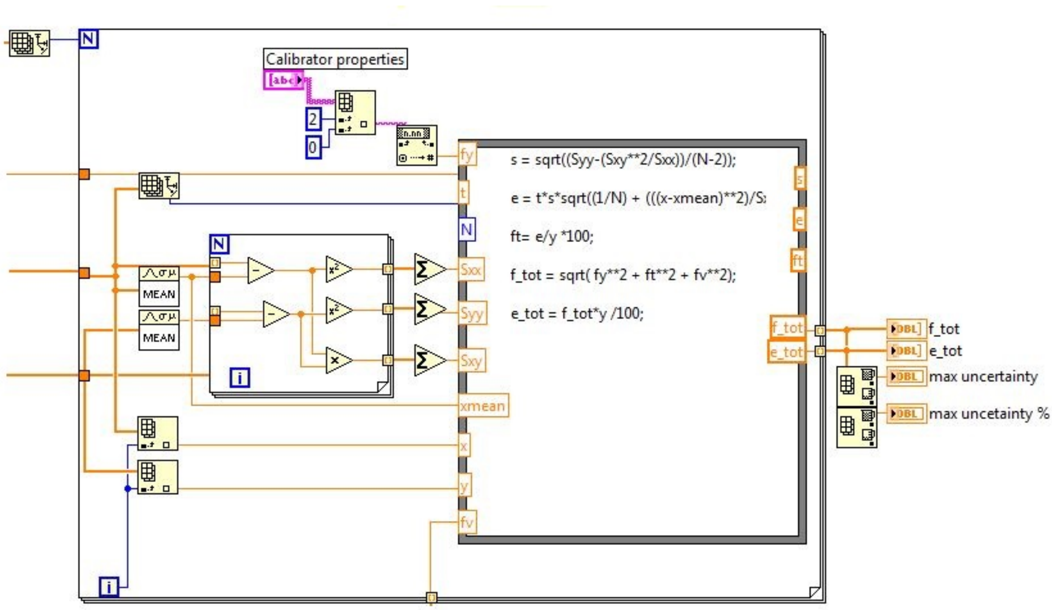

Figure 4.3: Calculation of random error

generates a HTML document that can be read in a browser, and saved as a pdf- file later. The case structure is shown in figure 4.4.

The report generator block is a subVI. Its inside is shown in figure 4.5. Here you can see the different variables and specifications is added to the report one by one. It is a long line of blocks with relatively few inputs, in order to make the main program cleaner the functions were put in a subVI. The report generator subVI include other subVIs, one where the calibration properties are gathered and rearranged to a presentable form for the report. An equivalent subVI for the calibrator properties and for the calibration summary are also made. These subVIs are shown in figure 4.6.

To check the linear equation, the estimated pressure is calculated and shown in the front panel. So if the estimated pressure deviates much from

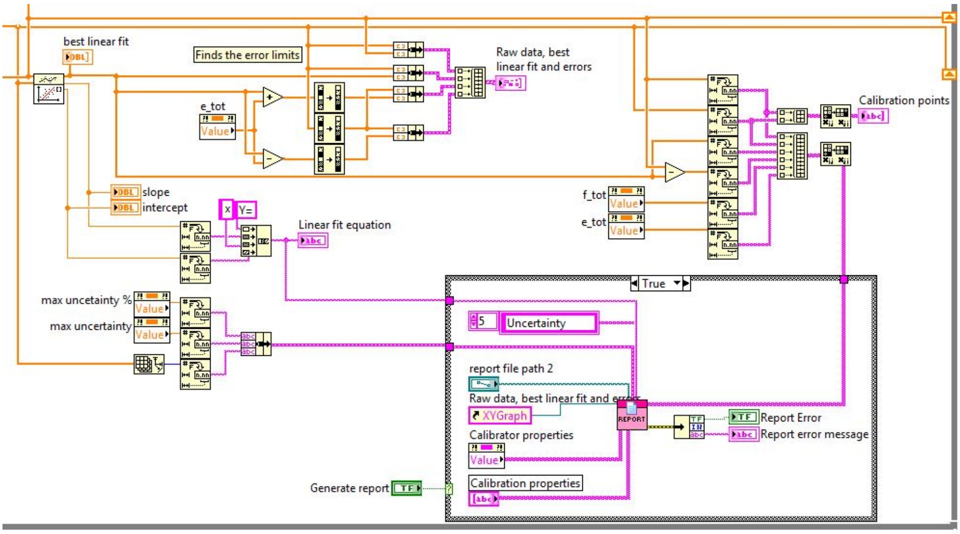

Figure 4.4: Arrays gatherd for the graph

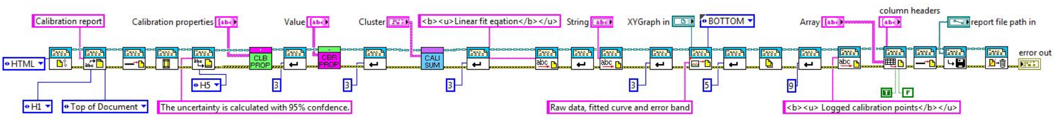

Figure 4.5: Generates the report

the real pressure, it is a sign that all is not ok.

4.2.2 User interface

The user interface, shown in figure 4.7, is build to fit a 22 inch screen. The mean Amplitude, the measured amplitude and the random error is graphed in the middle. This shows when the mean value is stable, and when the error is small enough to log the point. To the left, underneath the stop button, the properties for the calibration and the calibrator apparatus is filled in. Beneath is the clear-mean button, the log point button and the delete point button. The logged points are shown in the table at the bottom. Next to it, the linear equation and the pressure input terminals are shown. The large graph shows the raw signals, the linearizion and the errors. This graph is saved in the report. At the top the generate report button is shown along with the report path and error light and -text. To the right the student-t number is set, the uncertainties, slope, intercept and calculated pressure is shown.

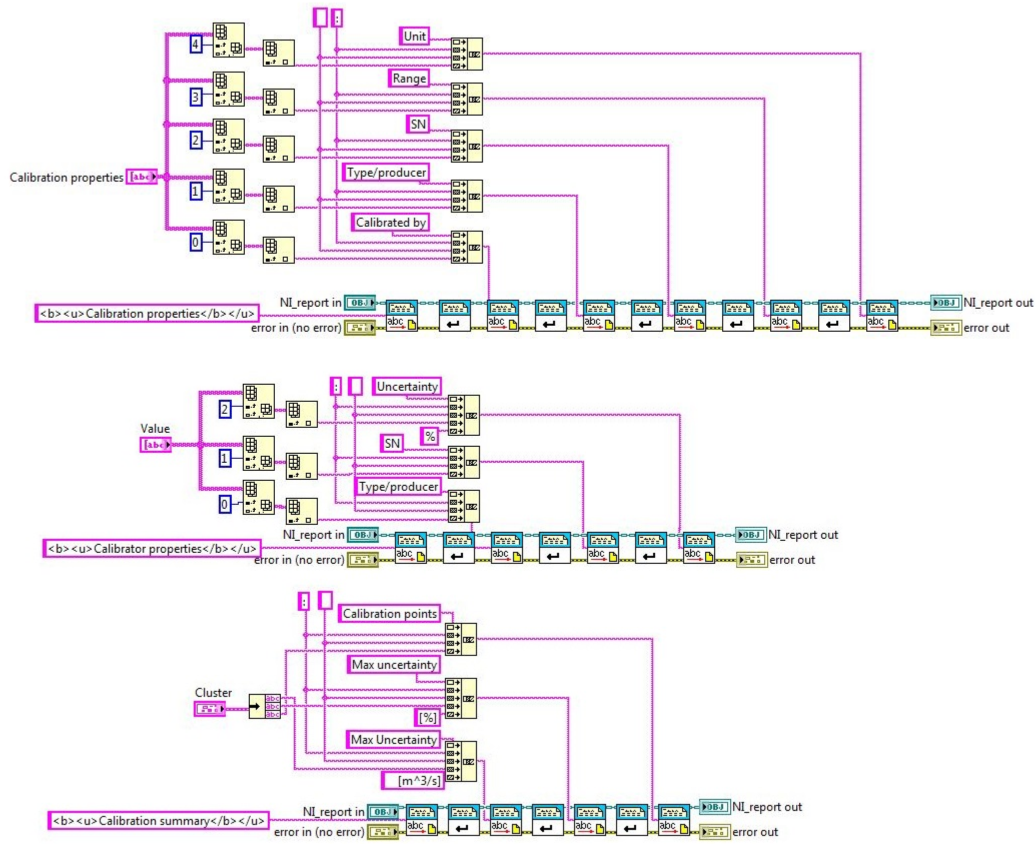

Figure 4.6: SubVI calibration properties

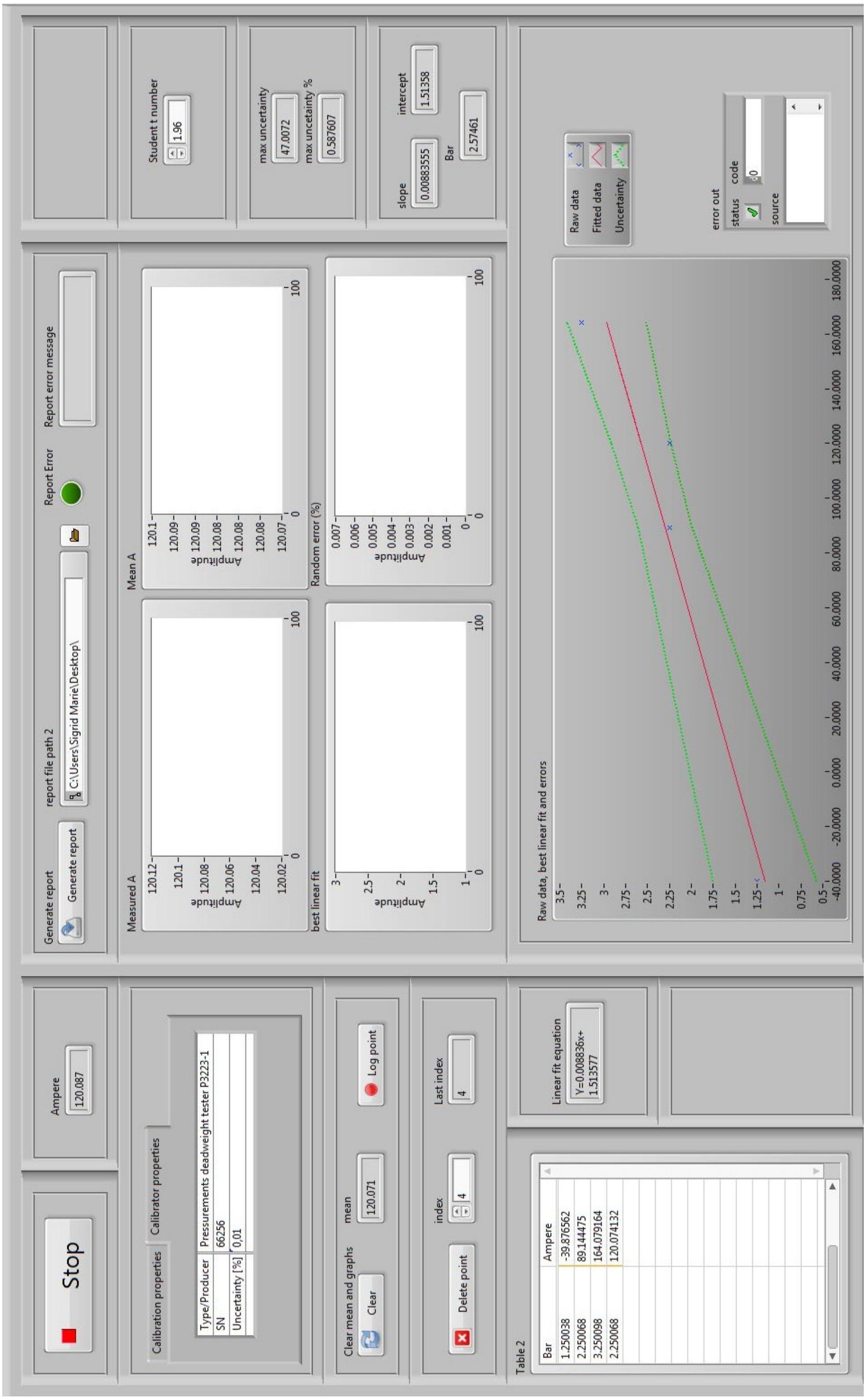

Figure 4.7: User interface

4.3 Dynamic modeling

The Kalman filter implementation in LabVIEW is a relatively simple operation when the models and parameters are correct, but can be cumbersome to debug and tune. Therefore it is important to be confident in the model and the other variables before trying to implement it. The LabVIEW filter has no error functions, and in the event of an error, the filter will either not run at all, or return NaN, without giving information of where the error is. The filter is also sensitive to dimension errors, this means that all the matrices and arrays must be in the right dimensions in order for the the filter to function.

The different filters has own LabVIEW functions, but they require different input. The Discrete Extended Kalman filter has been used in this thesis, because the nature of real time analysis is discrete, and our models are nonlinear. The filter require a noise model, a plant model, measurement input, a control vector and initial values.The Kalman filter is located in the Control and Simulation package, which is not a part of the basic LabVIEW functions.

4.3.1 FPGA

Because the Kalman filter and other control and simulation functions are only available in the Real Time module, the FPGA VI is relatively simple. It contains a flat structure that controls timing, and shows the values of the sensors. There is also a function that makes the FPGA-led blink in the same speed as the program iterations. This way you can see when the FPGA is running correctly. The FPGA program can be seen in figure 4.8.

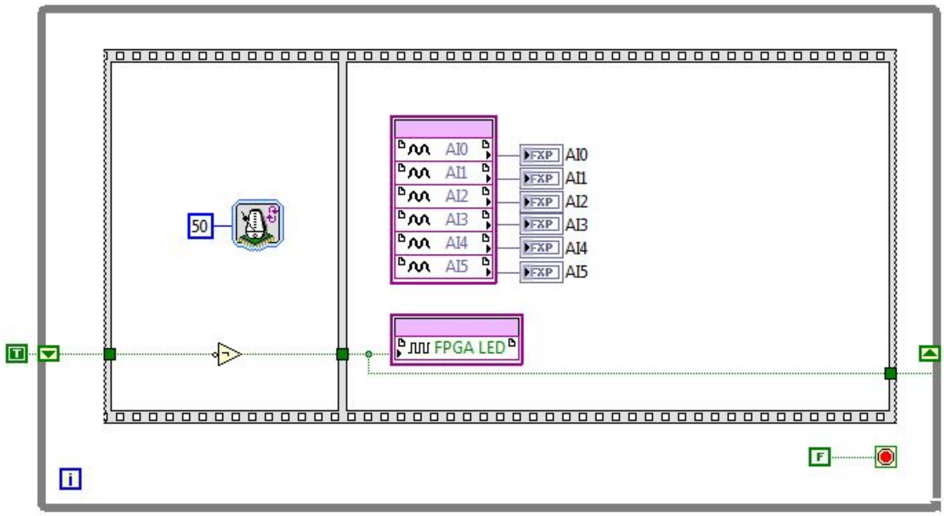

Figure 4.8: The FPGA code for the Kalman filter program

4.3.2 Real time

The simulation program implements the Kalman filter is inside a control and simulation loop. This loop is required for many of the simulation functions. The timing specifications is set in the top left corner of the loop, and can be set to run synchronous to the timing source, which in this case will be the real time target. The different parameters are plotted to visualize the filters function under operation. All the graphs are plotted towards the simulation time. Inside the Control and simulation loop other structures like while and for-loops are not allowed. The loop will also stop other functions outside the loop until the simulation is done. In order to implement the calibration constants and write the values to file, subVIs with the required loops are made. One for the calibration and one for the write to file operation. The subVIs can be seen in figure 4.9 and 4.10.

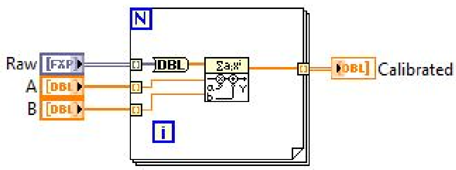

Figure 4.9: The calibration SubVI

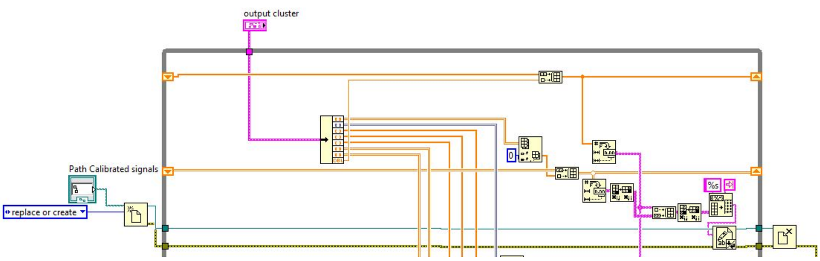

Figure 4.10: Parts of the write to file SubVI

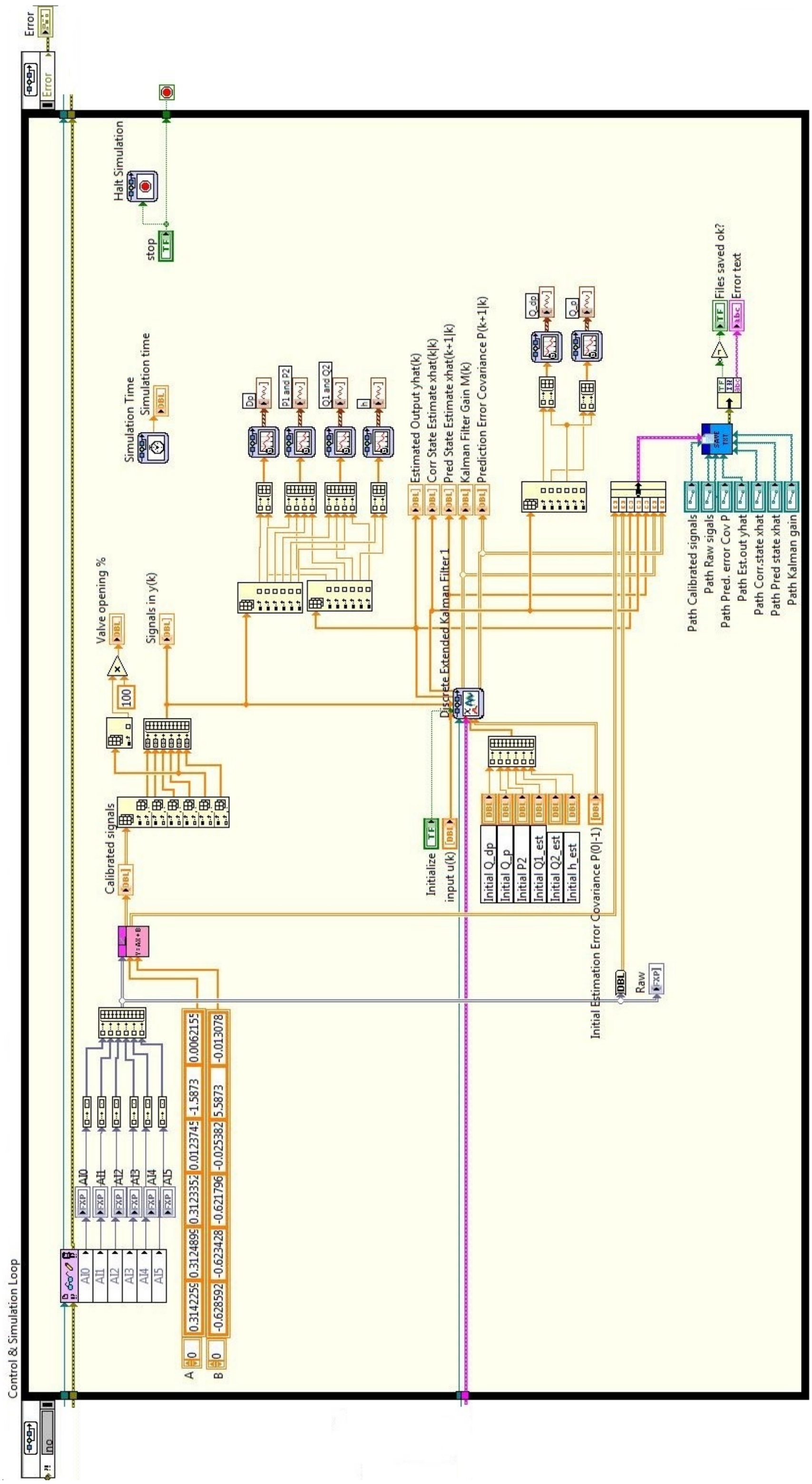

Figure 4.11: The control and simulation loop where the Kalman filter is implemented

The dynamic model is generated in a model-file. The discrete nonlinear plant model template from the LabVIEW library is the base for the model. It is shown in figure 4.13. The model is sent to the Kalman filter via a strictly typed static VI reference.

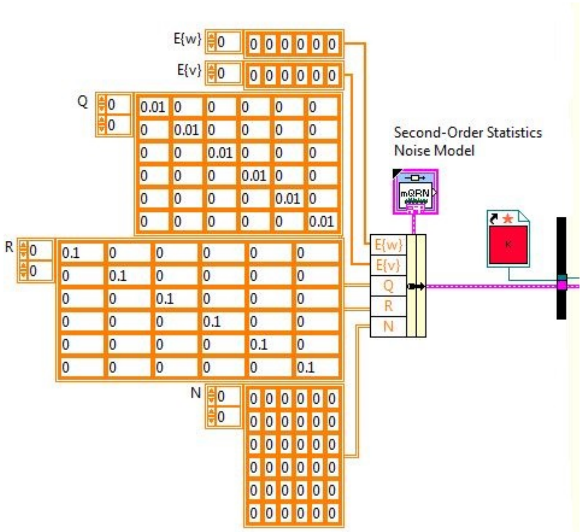

Figure 4.12: The noise model and the strictly typed VI reference to the Model

The noise model is a cluster of the matrices R, Q, N, E(v) and E(w), where N is the cross covariance matrix between the process noise vector and the measurement noise vector. If they are uncorrelated N is a matrix of 0. E(v) and E(w) are the expected values of the measurement noise and the process noise. The default is 0.

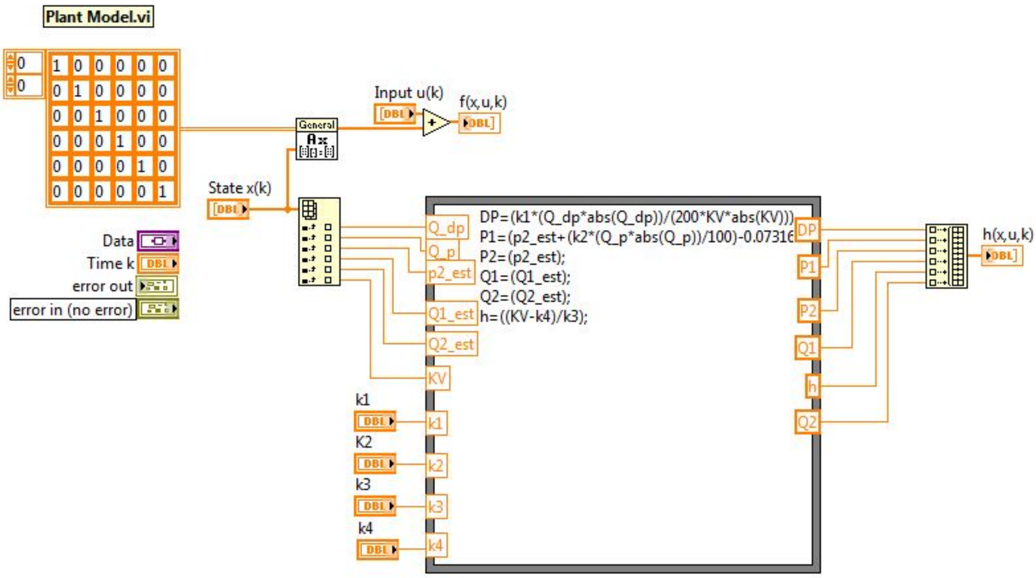

Figure 4.13: The Kalman filter model

4.3.3 User interface

The user interface on the real time program is made so that the operator is able to investigate the process. The user interface is not really necessary, and might claim some computer capacity. For real time programs that run in a stand alone matter, the user interface is not required.

The user interface is build to fit a 22 inch screen, there are tabs implementes, so that all the initial values can be set in the rear tab, and the simulation and logging results can be seen in the front.

Figure 4.14: The User interface for the Kalman filter program

Chapter 5

Experiment

5.1 Introduction

The experiment will be conducted on the swirl rig in the Water Power laboratory. The goal of the experiment is to see how well a real time modeling Labview program will behave. The Kalman filter, described in chapter 2, is implemented into LabVIEW, and logges the values from different sensors on the swirl rig. The experiment enables the verification of the model and the implementation in LabVIEW. This will show how the filter will behave when dealing with real life measurements and situations. The experiment will also show how well the Kalman filter will work when using models that are not completely accurate, on cases that are not so intricate. This will give a hint of how real life problems of larger scale must be handeled in order to get results that are satisfying.

The program requires that both logging and simulation are done simultaneously. A Real time project that is implemented on a RIO has the advantage of being able to run in a stand alone matter, but since this experiment is conducted in a lab with possibilities of monitoring and changing the system, there has been made a user interface to the program that enables the operator to monitor the results along the way. This way the operator is certain that the program and rig runs correctly and is able to monitor critical variables.

The experiment was conducted on several operating points to see how well the simulations will behave when changing the conditions. First to see how well the program went from initial conditions to good estimations, and then to see how the program responds to dynamics in the system.

5.2 HSE

To work in the Water Power a special net-based HSE course designed for the labs at EPT is required, in addition to a tour in the lab together with the HSE responsible to be oriented of the locations of the fire extinguishers, the first aid kits and other important features. Before an experiment is carried out, a risk evaluation has to be made and approved. An apparatus card must be placed on the rig at all times, and a work in progress sign must be hung on the rig under the experiments. The experiment must also be reported to the HSE responsible before starting. Important papers like procedures must be in a permian next to the rig. For own protection, protective glasses and hearing protection must always be used when experiment is running, and the operating procedures must be followed. The procedures are found in appendix A. The Apparatus card and Work in progress sign will be in Appendix **??**, along with the risk evaluation.

5.3 Equipment

Due to the late change of the RIO, the number of sensors were reduced. Only some of the calibrated sensors are used. Notice that the numbering on the sensors are changed for the same reason.

- 2 absolute pressure transmitters
- 1 Differential pressure transmitters
- 2 Flow meters
- A valve opening sensor
- A RIO with the correct LabVIEW programs and modules.
- A switch and network cables

- A host computer

5.4 The case

To see how the Kalman filter works for different approaches there has been established a test case. Q will be estimated both fromΔP and P_1 - P_2. The sensor location can be seen in 5.1. The two cases made into model files in LabVIEW, so the model can easily be changed if other cases are tested.

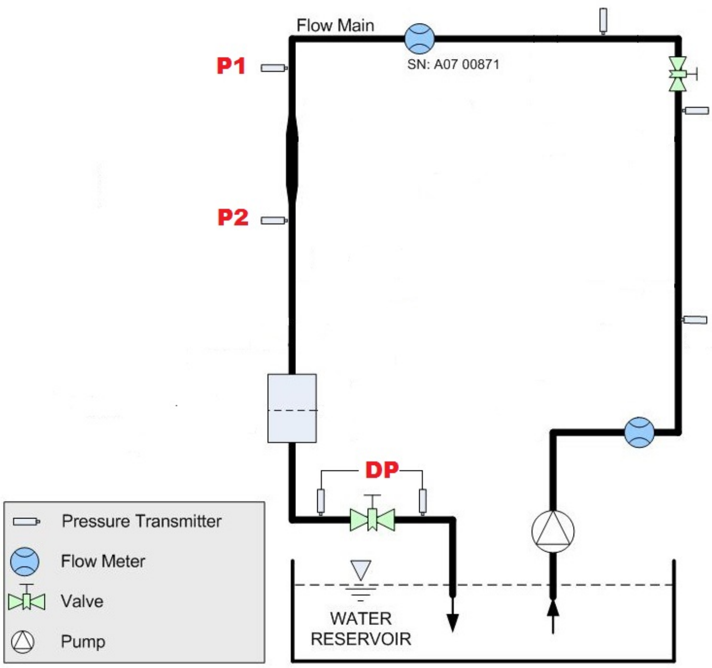

Figure 5.1: The sensor location, modified from [2]

The Kalman equations:

$$x_{k+1} = f(x_k, u_k) + Gw_k \tag{5.1}$$
$$y_k = h(x_k, u_k) + Hv_k \tag{5.2}$$

The flow is estimated based on the pressure measurements. The measurements are:

$$y_k = \begin{bmatrix} \Delta P \\ P_1 \\ P_2 \\ Q1 \\ h \\ Q2 \end{bmatrix} \tag{5.3}$$

The states are the paramenters that are calculated by the filter. Only the two first of the parameters are calculated by the use of equations, the rest are estimations of themselves. They are included for controlling purposes, so that any deviations can be investigated further.

$f(x_k, u_k)$ will become:

$$f(x_k, u_k) = \begin{bmatrix} Q_{dp} \\ Q_P \\ P2_{est} \\ Q1_{est} \\ Q2_{est} \\ KV \end{bmatrix} \tag{5.4}$$

The equations are derived from loss equations and Bernoulli.
$h(x_k, u_k)$ will be:

$$h(x_k, u_K) = \begin{bmatrix} \frac{\rho K1 Q_{DP}^2}{2*10^5 (KV)^2} \\ p2_{est} - \frac{\rho g h}{10^5} + \frac{K2 \rho Q_p^2}{2*10^5} \\ P2_{est} \\ Q1_{est} \\ Q2_{est} \\ \frac{KV - K3}{K4} \end{bmatrix} \tag{5.5}$$

Where the Ks are constants.
In the extended Kalman filter the equations are linearized in the current state automatically. The linearizion is done by taking the partial derivation of the equations in the current state.

In order to implement the Kalman-filter in LabVIEW, the auto covariance matrix for the noises, R and Q are needed for the noise model.

The matrix R will be:

$$R = \begin{bmatrix} r_{11} & 0 & 0 & 0 \\ 0 & r_{22} & 0 & 0 \\ 0 & 0 & \vdots & 0 \\ 0 & 0 & 0 & r_{ii} \end{bmatrix} \tag{5.6}$$

Where r_{ii} is the variance of the measurement noise. Q is similar, only the variables are the variance is from the process.

The equations were inserted into the model in LabVIEW.

5.5 Test spesification

The experiment was run on three different operating points to see how well the Kalman filter handled the changes. The rig was run at every operating point for two minutes to make sure the values had time to stabilize. The rig was run at approximately:

- 25 l/s
- 29.5 l/s
- 20.5 l/s.

The following parameters were chosen:

- Initial values - All initial values were set to 1 for simplicity. The calculations will converge faster with a more accurate value, but they will end up the same
- Initial predicted covariance - The p_{ii} values in the matrix were set to 1. The values must be nonzero in order for the filter to have any gain.
- Measurement error - The r_{ii} values were estimated to be 0.1.
- Process error - The q_{ii} values were set to 0.01.

Chapter 6

Results

6.1 The measurements

The measurements were logged and analyzed by the Kalman filter LabVIEW program presented in chapter 4. The results were written to text files on the single board RIO, and collected at the end of the experiment

The goal of the experiment is to estimate the flow based on the pressure loss from both the back-pressure valve and the pressure loss over the swirl generator, but also to investigate all the different parameters in order to gain a better understand how the filter treats them.

The estimated flow based on the pressure loss over the valve is plotted in figure 6.1 and 6.2 along with the measured flow. The results were parted into one graph for the first 20 measurement, and one for the rest of the simulation. The first 20 measurements show the converging from the initial values, and is therefore separated from the rest, in order to visualize the different effects. As can be seen in the last part of running at around 29 l/s the flow mysteriously increased without changing any of the parameters like the valve opening. The results were a bit interesting, so the results were kept.

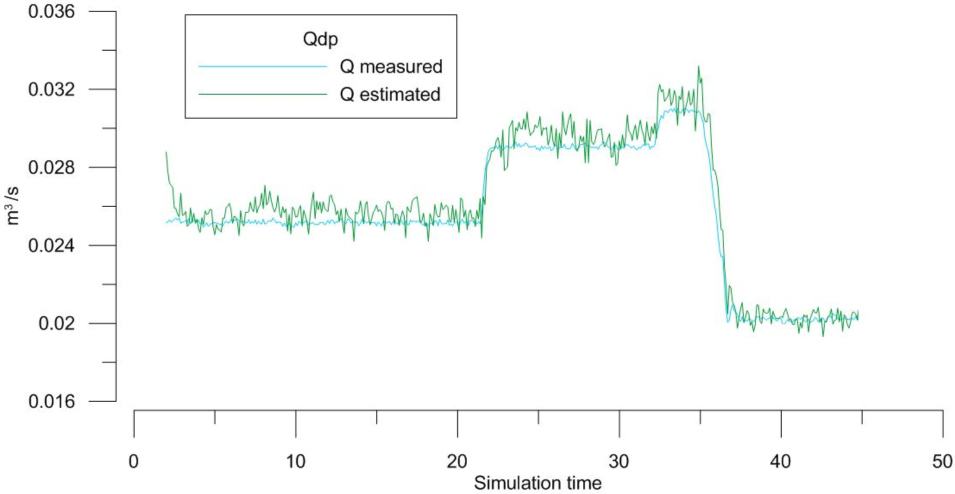

Figure 6.1: Qdp and Q measured

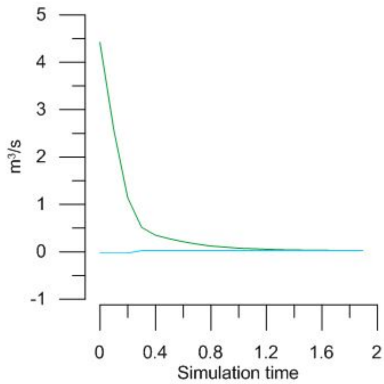

Figure 6.2: Qdp and Q measured the first 20 measurements

The Kalman filter shows the calculated $\hat{y}$, this way the deviation from the actual measured values can be found. A comparison between the measured ΔP and the estimated ΔP is found in figure 6.3 and 6.4. The first 20 measurements are again plotted by themselves. The estimated values are quite similar to the measured except from a small time delay.

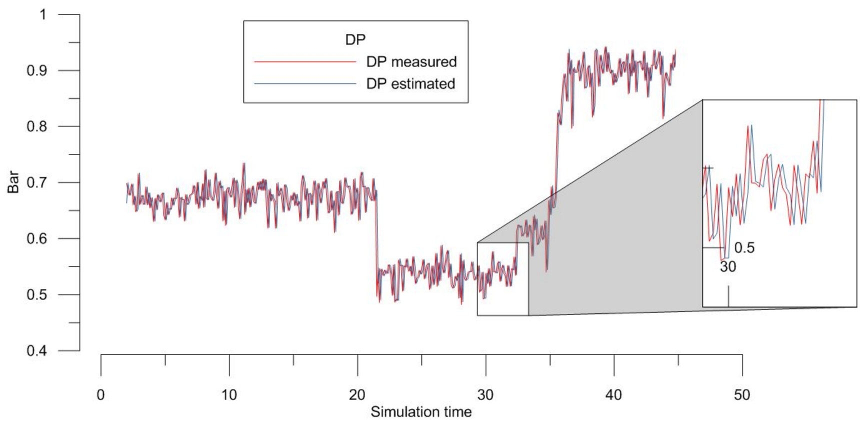

Figure 6.3: ΔP estimated and real

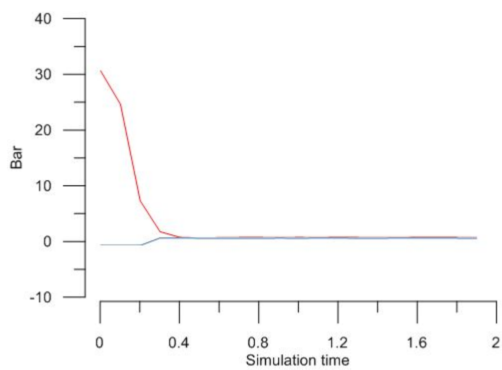

Figure 6.4: ΔP the first 20 measurements

The Kalman gain is multiplied with the deviation between the measured and estimated y-value, and is a matrix that changes with time. The gain for the first spot in the first row is presented in figure 6.5 and describes Δ P in the first equation. The graph is plotted without the first 20 measurements. The graph 6.6 shows the gain for the fourth spot in the fourth row, which represents the relation Q1 has to its own estimate $Q1_{est}$.

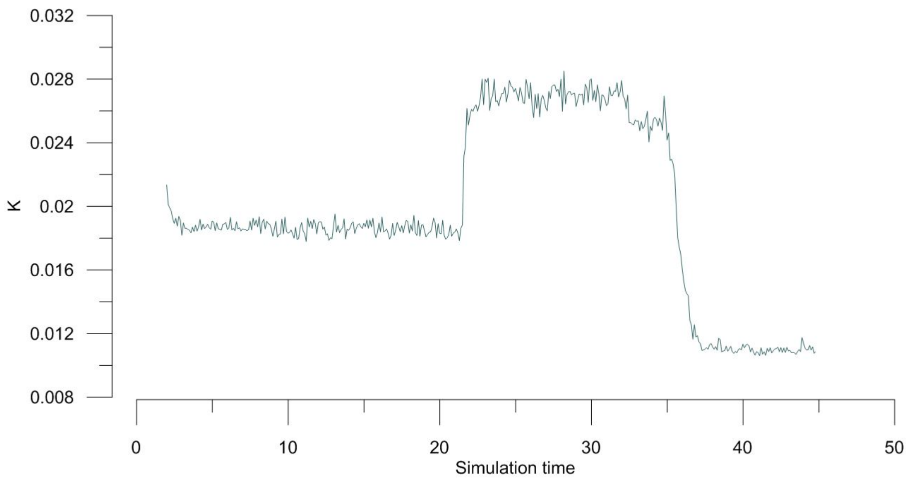

Figure 6.5: The kalman gain for the estimation of Qdp

Some of the measurements in the measurement vector is set to be equal to their own state, in order to see how the Kalman filter treats them. The comparison between P2 and $P2_{est}$ can be seen in figure 6.7. A small part is enlarged so the differences are visualized.
The Estimate of Q based on the pressure loss from P1 to P2 did not turn out very good. The result is shown in figure 6.8. A possible explanation is discussed later.

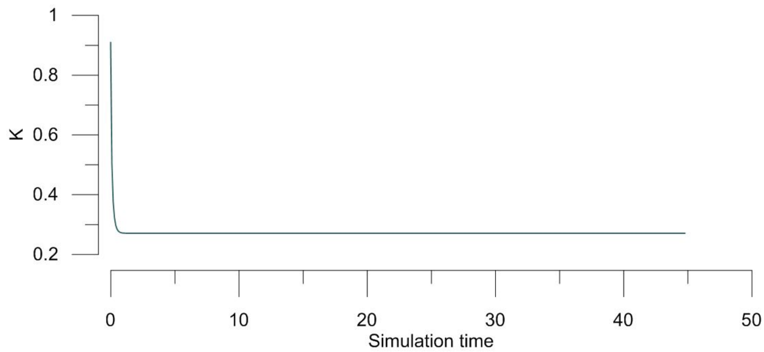

Figure 6.6: Kalman gain for the measured Q

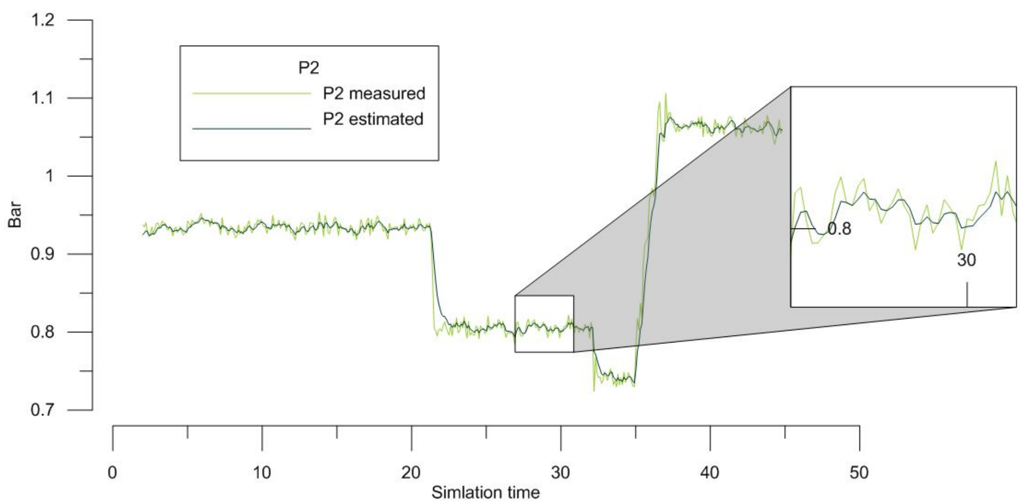

Figure 6.7: The measured P2 and filtered P2

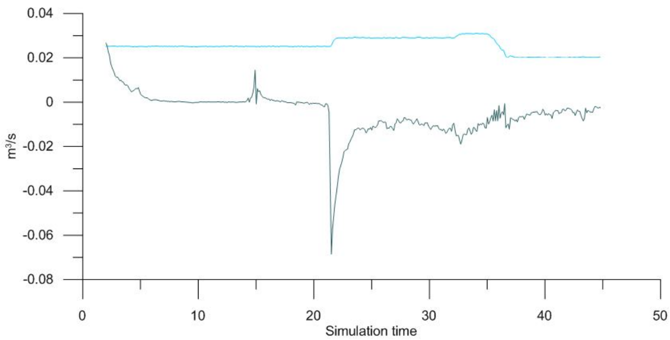

Figure 6.8: Qp

Chapter 7

Discussion

The experiments on the swirl rig were conducted in order to investigate how well the Kalman filter worked. The cases used were relatively simple, and the results were expected to be thereafter, though the results should show the basic principle.

The results from the estimations of Qdp has quite a bit of noise. There could be several explanations for this. If the graph for ΔP is investigated, it is clear that these measurements are noisy compared to the ones from the flowmeter, this will partly contribute to the large noise of the estimation. In addition, the Q matrix will contribute to noise if the values are set too high. Q was set to be 0.01. The model is somewhat simple and not completely trusted, and the Q was therefore not set any lower. If the Q is too high, the filter will "trust" the measurements more than the model and will therefore contribute to more noise. A lower process noise matrix would probably calm the noise, but because of the noisy ΔP signal, the effect would perhaps be limited.

The effect from Q is also visible in the plot 6.7 for P2. The noise from the measurements are reduced some in the estimation, but could probably been reduced even more. A smaller Q would also result in slower convergence from initial values. As can be seen in the plot fo the first 20 seconds of both flow and pressure measurements, the convergence happens within the first few measurements.

In order to get better results for the estimated values, more redundancy to the systems could be added, this by the use of differential equations, more measurements or more equations for the flow. This could contribute to less noise, and more accurate results. The current model would also be improved by a more sophisticated noise model and optimized constants.

For the sudden increase in the flow, the model seems to regulate the estimations in a correct manner, even though the valve opening is constant. When comparing the Kalman gain for the first equation it follows the same pattern as Q, except from where the mysterious increase in flow appear, where the Kalman effect is the opposite. The effect can perhaps be explained by the H-Q diagram seen in figure 7.1. When the flow is changing because of more or less opening of the valve, the loss and flow will follow the red linear line, but when the flow is increased with a constant valve opening the flow and head will follow the black arrow up or down the current H-Q line, and thus move in a opposite manner of the red line.

The Kalman gain for the figure 6.6 shows the gain for Q=Q_{est}. The gain will rapidly converge from initial values, and then stabilize. As the estimate is only dependent of the one measurement, the gain will find the relation between the two.

The flow estimation based on P1 and P2 did did not turn out very good. A possible explanation is that the loss in the swirl generator is quite small, in the order of magnitude or smaller than the noise in the measurements. This makes the losses disappear in the noise, and the calculations will be subsequently bad. The estimations does not give any reasonable answer even with changing the parameter. Non of the trials has lead to good results. This gives an indicator of the weakness in the simplified model when the parameters in question are non significant. In order to increase the quality of the results the model could be made by the use of the systems differential equations. This will increase the systems observability and redundancy by adding more equations for the states.

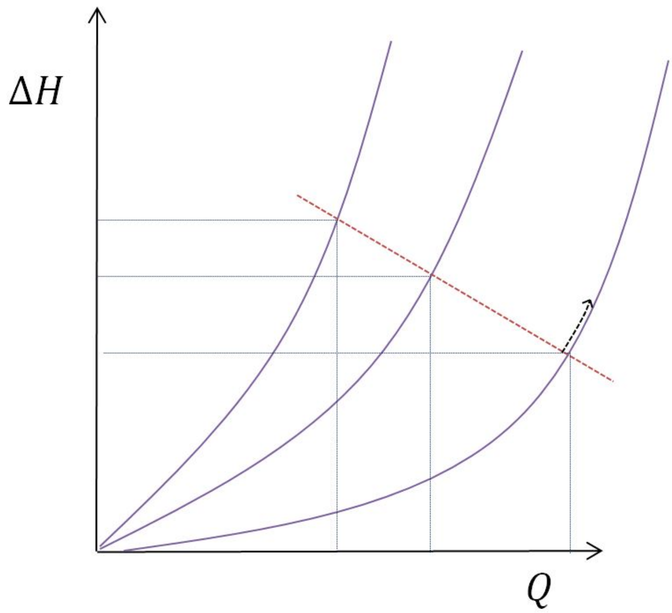

Figure 7.1: The relation between ΔH and Q for different operating points

Chapter 8

Conclusion

The focus of this thesis has been learning and understanding the theory behind real time modeling. This is a large subject, so the area was limited down to one particular method, namely the Kalman filter. A thorough investigation is made for the basic theory of the filter, the equations for the linear case are derived, and the different parameters explained, in order to increase the understanding of how the filter does the estimations. This knowledge came in quite handy when implementing the filter into LabVIEW. Even though the author had some knowledge of LabVIEW, the control and simulation package had never been used. This package opened a new world of control and simulation possibilities.

When making a program from scratch there are always possibilities of implementing errors. Therefore, validation and verification is of great importance. First to check that the method implemented in the program is applicable, but also that the program and method is used the correct way. Small errors that are large enough to affect the results, but are too small to crash the program, are easy to implement, but hard to discover. The results from such a program must therefore be treated with some caution. The programs presented here have been tested on several different operating points and tested for strength and weaknesses. There will always be improvements to be made, but for the application in this thesis the program seemed to run satisfactory. When tested, the programs seemed to respond according to theory. This is a good indication that the methods are implemented correctly.

Instead of building a test-section from scratch, it was considered better to modify one of the existing rigs for the experiments. The existing swirl rig at the Water Power lab was modified to fit the experiment specifications, and proved to be a very good rig for testing modeling scenarios due to its many ways to change the operating points. The modifications that were made were the changing of the back pressure valve to one that could be operated from the second floor, and the welding of more pressure outlets. Both these changes will make the rig better to use for other experiments as well, by adding more locations to measure pressure, and to control the pressure and flow in the rig much easier than before.

The estimations in the experiment shows a relatively good result for applications where the measured values are significant in the calculations of the estimated value. The simulations follow the measurements relatively well, even though the estimations are noisy and not completely on the spot at all times, as seen in figure 6.3. The noise and errors could be decreased if the parameters of the noise model and constants were optimal, or the system had more redundancy. Still, the results clearly show the desired results, the estimations for the flow follows the real values as seen in figure 6.1, and the noise in the measurements were reduced as seen in figure 6.7.

The estimation of Qp shows that if the measured values are non significant for the estimations, the result will be rather bad. In those cases, the estimations must be based on a better model with more observability. This type of case is relevant for the hydro power industry as many of the estimations could be based on small pressure and temperature differences. It is very interesting to find both cases that work and those who don't, they increase the understanding of how this work can be continued.

Even though this thesis show a rather simple model, the results imply that the Kalman filter could have a potential to be a useful tool for the estimations of parameters in the hydro power industry.

Chapter 9

Further work

The investigation of how the Kalman filter works on flow problems, are full of aspects that could be tested. The method and model presented here is merely the beginning of what could end up to be what could be successfully implemented in a hydro power plant.

As the model and parameters presented here were relatively simple, there are several ways to improve the results, some of these are:

- Make a more sophisticated model.
- Optimize the constant in the current model.
- Investigate good values for the noise model.
- Add a control function to the model.
- Add more redundancy or observability to the system
- Add more measurements or parameters, this would require a RIO with more input terminals.
- Investigate the effect of initial values.

in order to get better results for the estimation of Qp, some changes in the model would be required. Preferably use a more accurate model, maybe differential equations to improve the redundancy and observability. This could be a very interesting, to see how good the model had to be in order to get a decent result.

The LabVIEW program where the filter is implemented seems to work according to the specification. There will always be improvements to this type of program, but for this use the program seemed to run well, there are still many improvements to make, and a even better Kalman filter program in labview would increase its usage

If the equipment for control systems were available, it could be interesting to try to implement control functions based on the Kalman filter calculations, this would probably require a more elegant model.

Yet another interesting application would be to try to implement the Kalman filter on a real power station, or on the Francis rig at the Hydro power lab. This would probably require the model and parameters to have higher quality than what is presented in this thesis, but the results would without a doubt be very informative.

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Appendix A

Procedures

A.1 Operating Procedure for Swirl rig

This procedure is a rewrite of the procedure written by Jarle V. Ekanger.

Before start up

1. Make sure all the valves are in correct position, so that the water goes to the swirl rig and not the Pelton-rig. See figure A.1 for reference. Green valves are open, black are closed.

2. The pump is controlled from the small window "Pelton pump/gen". The pump set point should be at 100 rpm before start up. The pump is controlled by the buttons to the right and left for the set point window.

Start up

1. The pump must be at 500 rpm before the water is let into the rig

2. When starting, the rig must be emptied for air. Follow the procedure in step 3-10.

3. Open valve V3 (this may be left open the entire start-up).

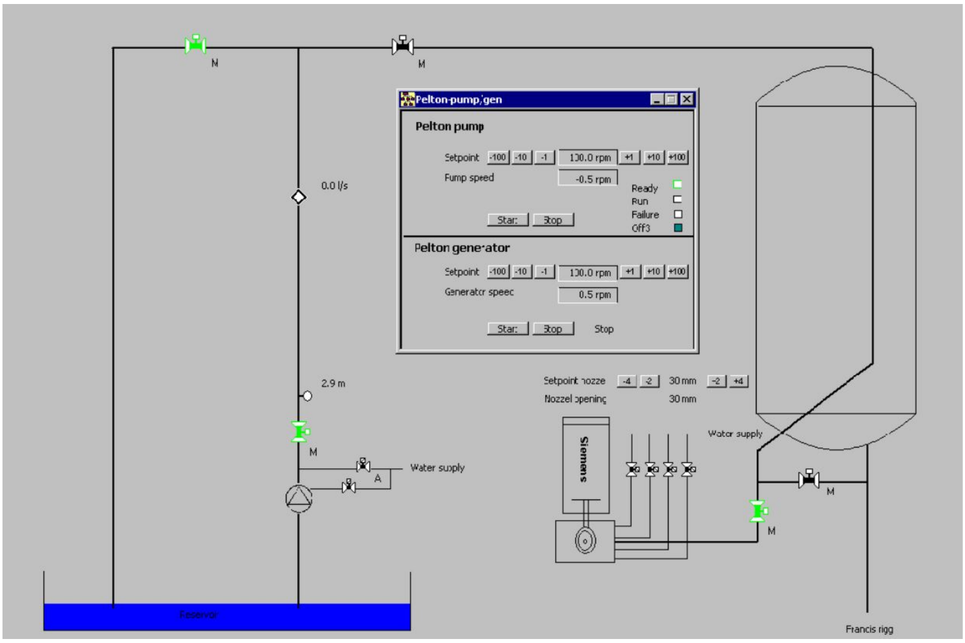


Figure A.1: Owerview of valves

4. Open the vent valves L1 and L2, and close the backpressure valve VT completely.

5. To fill the rig with water, drive the pump to 600rpm.

6. When the water surface is above the Plexiglas section, control that V2 is open and close valve V1 and vent valve L1.

7. When there is a continuously water stream through L2, close L2 and open L1. Then open V1 and closes V2. Hopefully all air is now above the pipe where V2 and L2 is mounted, and will be vented through L1. When there is a continuously water stream in L1 the system is emptied of air.

8. Left over air can be vented by opening V1 and V2 so that the flow approaches maximum. Make sure that the venting valves are closed before opening the back pressure valve. If the static pressure drops

below the atmospheric pressure, air will be sucked in, and the venting will have to be repeated.

9. Open the back pressure valve VT in small steps. Adjust the valves and the pump until the desired operating point is found.

10. If the nozzle is not in use, remember to close valve V3.

Operation

1. To adjust operating point, adjust the back pressure valve VT, V2 and V1 (and V3 if in use).

2. Remember that by adjusting one valve, this will affect the operation point of the rest of the rig. The loss coefficient can become large when dealing with low flow and when the valves are almost closed.

Shutting down

The pump speed should be reduced to 100 rpm before shutdown.

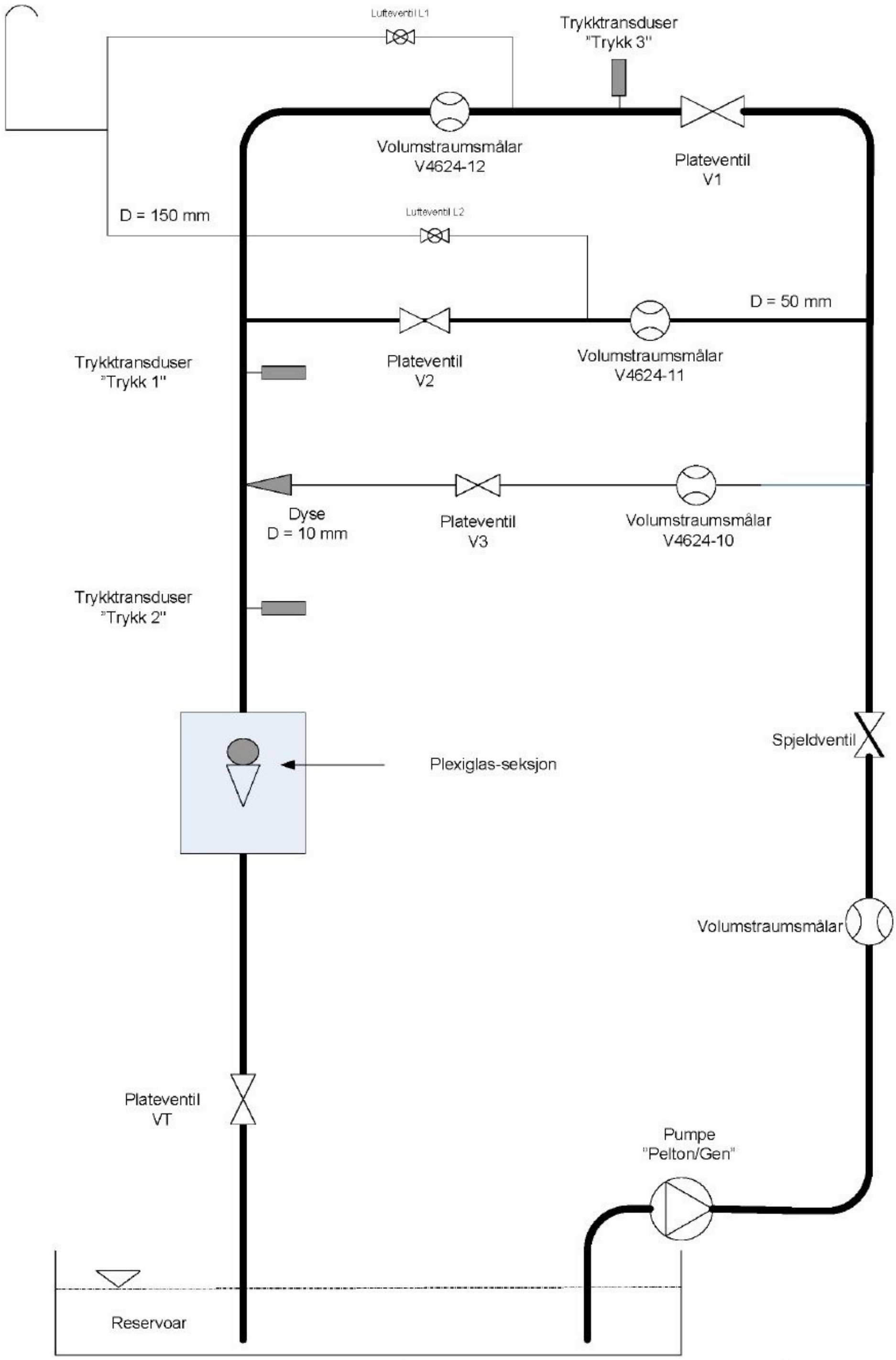


Figure A.2: Valves

A.2 Procesure for calibrating the pelton flow meter to the calibration tank

Before start up

1. Open the valve from the pelton basin and the francis basin. The water will be taken in from the pelton basin, but out in the francis basin, so if the valve is cosed the pelton basin will be emptied.
2. Make sure that nothing is leaning towards the calibration tank, and loosen the three legs of the tank.
3. Make sure that all valves are in the right position. Some valves above the inlet of the calibration tank must be handled manually. The rest can be operated from the control room.
4. Before starting the pump it must be primed, or filled with water. There are own small valves for this next to the pump.
5. The pump set point must be set to 100 before start up.
6. Set the flow points you want to test, and calculate the time you need in order to get at least 1000-1500kg in the tank.

Operation

1. Start the pump, and slowly increase the speed until you find your first measuring point. The approximate flow is given in the governing program.
2. Read the measurements you need, the before weight, temperature for both water and air, air pressure.
3. Set the timer on the tilting valve. If calibrating alone, set the waiting time to as long as you need to get back to the control room before the valve activates. The best would be to get some help from a friend (with a walkie-talkie), so that there is one by the valve and one in the control room.
4. When the measurements are taken, timer is set and the flow is right, press play. The screen will make a lot of noise, so wear ear protection.

5. When the valve activates, press clear in the calibration program, and when it closes, log the point.
6. Read the new weight of the calibration tank, and update the values for the next measurement. Repeat step 2-6 for all the flows.

subsubsectionShut down

1. Reduce the pump speed to 100 rpm before it is shut down.
2. Fasten the tank legs and close the valves between the basins.
3. Insert all the values into the calibration excel document.

Appendix B

Calibration rapports

B.1 Optiflux 2000 F A051090

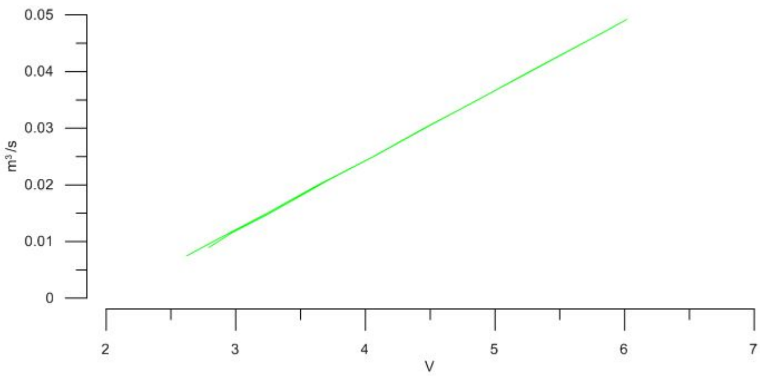


Figure B.1: The calibration curve for Optiflux 2000 F A051090

Linear equation

$$y = 0.012345462x - 0.025160210 \tag{B.1}$$

Ambient pressure [hPa]	Water temp [oC]	Density of water [kg/m3]	Density of air [kg/m3]
100.47	12.6	999.4904	1.2030
100.47	12.54	999.4979	1.2024
100.49	12.61	999.4892	1.2030
100.52	12.85	999.4589	1.2044
100.52	12.88	999.4551	1.2044
100.52	12.91	999.4512	1.2045
100.52	12.94	999.4474	1.2045
100.54	12.97	999.4435	1.2047
100.55	12.98	999.4422	1.2047
100.56	13.01	999.4383	1.2047
100.56	13.14	999.4213	1.2042
100.56	13.16	999.4187	1.2043
100.55	13.19	999.4147	1.2041
100.55	13.21	999.4121	1.2038
100.55	13.22	999.4108	1.2037
100.57	13.23	999.4095	1.2042
100.58	13.24	999.4081	1.2046
100.6	13.25	999.4068	1.2050
100.6	13.24	999.4081	1.2049
100.59	13.28	999.4028	1.2048
100.6	13.25	999.4068	1.2046

Table B.1: Calibration of Large flowmeter

Differential weight		Calculated Flow Rate	Manual Observation
[kg]	[s]	[m3/s]	[V]
1334.1	150.12	0.0089020	2.795036
1383.6	120.101	0.0115396	2.975159
1482.4	100.100	0.0148346	3.256084
2094.2	100.101	0.0209573	3.729268
1751.5	70.100	0.0250296	4.070979
2143.3	70.102	0.0306278	4.515252
1740.2	50.104	0.0347937	4.856295
1572.8	40.103	0.0392890	5.220669
1777.4	40.105	0.0443959	5.635692
1882.5	40.102	0.0470259	5.850855
1968.3	40.103	0.0491681	6.019584
1875.1	40.104	0.0468398	5.836806
2244.9	50.104	0.0448858	5.674217
1988.6	50.104	0.0397608	5.254117
2432.5	70.103	0.0347609	4.855285
2098.9	70.104	0.0299933	4.45833
2473.6	100.103	0.0247548	4.04801
1987.9	100.106	0.0198933	3.632953
1488.9	100.102	0.0149001	3.241117
1213.9	120.105	0.0101249	2.841902
1104.5	150.105	0.0073717	2.619291

Table B.2: Calibration of Large flowmeter

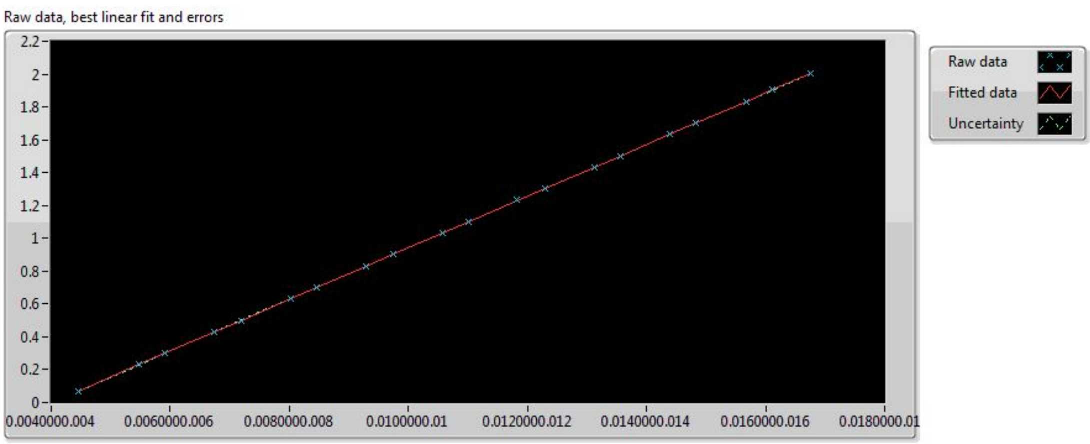
Calibration report

Calibration properties
Calibrated by: Sigrid Marie Skodje
Type/producer: FCX
SN: 9602 N 0004 CK1
Range: 2.5bar a
Unit: bar

Calibrator properties
Type/producer: Pressurements deadweight tester P3223-1
SN: 66256
Uncertainty: 0.01%

Calibration summary
Max Uncertainty: 0.000803[bar]
Max uncertainty: 1.145053[%]
Calibration points: 20

Linear fit eqation
Y=157.112975x-0.628592



Logged calibration points

Pressure	Ampere	Best linear fit	Deviation	Uncertainty %	Uncertainty
0.070106	0.004450	0.070598	-0.000492	1.145053	0.000803
0.230347	0.005465	0.230063	0.000284	0.307975	0.000709
0.300453	0.005915	0.300723	-0.000270	0.222935	0.000670
0.430650	0.006741	0.430483	0.000167	0.139555	0.000601
0.500755	0.007188	0.500668	0.000087	0.113139	0.000567
0.630952	0.008018	0.631164	-0.000212	0.080725	0.000509
0.701057	0.008456	0.699900	0.001158	0.068890	0.000483
0.831254	0.009292	0.831285	-0.000031	0.053592	0.000445
0.901360	0.009741	0.901832	-0.000472	0.047854	0.000431
1.031556	0.010576	1.033106	-0.001550	0.041089	0.000424
1.101662	0.011012	1.101480	0.000181	0.038713	0.000426
1.231858	0.011829	1.229935	0.001923	0.035636	0.000439
1.301964	0.012288	1.302071	-0.000108	0.035190	0.000458
1.432160	0.013124	1.433412	-0.001252	0.035469	0.000508
1.502266	0.013557	1.501325	0.000941	0.035226	0.000529
1.632462	0.014399	1.633707	-0.001244	0.036416	0.000594
1.702568	0.014827	1.700955	0.001613	0.036729	0.000625
1.832765	0.015667	1.832863	-0.000098	0.038133	0.000699
1.902870	0.016112	1.902779	0.000092	0.038777	0.000738
2.003021	0.016754	2.003739	-0.000717	0.039855	0.000798

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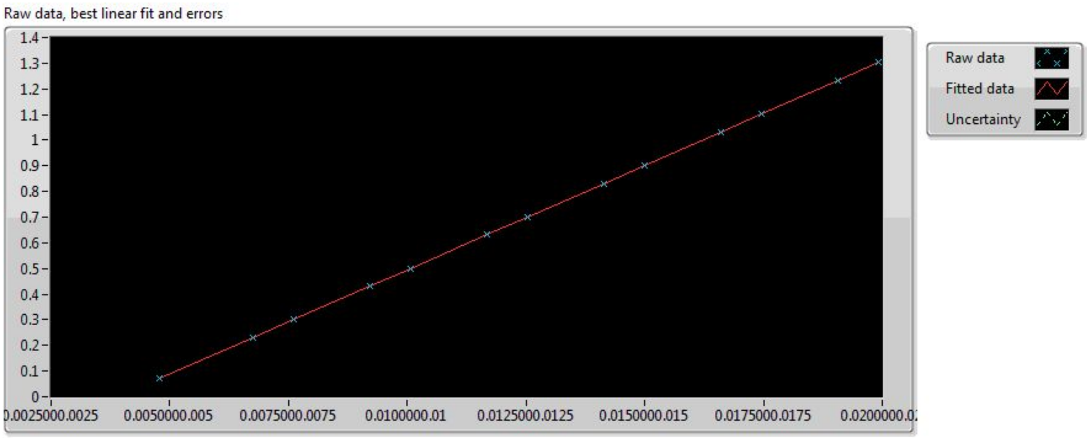
Calibration report

Calibration properties
Calibrated by: Sigrid Marie Skodje
Type/producer: FCX
SN: A5A5304F
Range: 1.3 bar
Unit: bar

Calibrator properties
Type/producer: Pressurements deadweight tester P3223-1
SN: 66256
Uncertainty: 0.01%

Calibration summary
Max Uncertainty: 0.000170[%]
Max uncertainty: 0.162098[bar]
Calibration points: 13.000000

Linear fit eqation
Y=81.391035x+-0.319467



Logged calibration points

Pressure	Ampere	Best linear fit	Deviation	Uncertainty %	Uncertainty
0.070106	0.004785	0.069960	0.000146	0.162098	0.000114
0.230347	0.006755	0.230308	0.000040	0.041781	0.000096
0.300453	0.007617	0.300482	-0.000028	0.030097	0.000090
0.430650	0.009217	0.430744	-0.000095	0.019462	0.000084
0.500755	0.010077	0.500747	0.000009	0.016678	0.000084
0.630952	0.011678	0.630986	-0.000034	0.013709	0.000086
0.701057	0.012540	0.701159	-0.000102	0.012974	0.000091
0.831254	0.014138	0.831240	0.000014	0.012426	0.000103
0.901360	0.015002	0.901553	-0.000193	0.012350	0.000111
1.031556	0.016599	1.031510	0.000046	0.012405	0.000128
1.101662	0.017460	1.101606	0.000056	0.012520	0.000138
1.231858	0.019058	1.231672	0.000186	0.012778	0.000157
1.301964	0.019922	1.302008	-0.000044	0.013054	0.000170

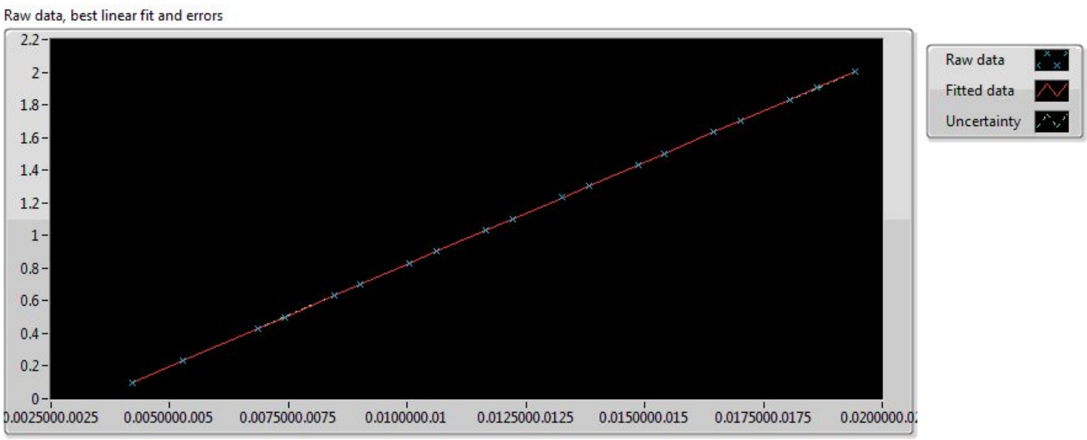
Calibration report

Calibration properties
Calibrated by: Sigrid Marie Skodje
Type/producer: FCX-AII
SN: A5E7992F
Range: 2 bar
Unit: bar

Calibrator properties
Type/producer: Pressurements deadweight tester P3223-1
SN: 66256
Uncertainty: 0.01%

Calibration summary
Max Uncertainty: 0.000356[%]
Max uncertainty: 0.318891[bar]
Calibration points: 19.000000

Linear fit eqation
Y=125.185811x+-0.427860



Logged calibration points

Pressure	Ampere	Best linear fit	Deviation	Uncertainty %	Uncertainty
0.100151	0.004216	0.099886	0.000266	0.318891	0.000319
0.230347	0.005262	0.230807	-0.000460	0.125483	0.000289
0.430650	0.006861	0.431063	-0.000413	0.057388	0.000247
0.500755	0.007418	0.500817	-0.000061	0.046814	0.000234
0.630952	0.008456	0.630749	0.000202	0.033860	0.000214
0.701057	0.009014	0.700534	0.000524	0.029216	0.000205
0.831254	0.010054	0.830697	0.000556	0.023171	0.000193
0.901360	0.010620	0.901591	-0.000231	0.020971	0.000189
1.031556	0.011658	1.031550	0.000006	0.018253	0.000188
1.101662	0.012222	1.102184	-0.000522	0.017386	0.000192
1.231858	0.013256	1.231611	0.000247	0.016428	0.000202
1.301964	0.013819	1.302062	-0.000098	0.016290	0.000212
1.432160	0.014858	1.432130	0.000031	0.016100	0.000231
1.502266	0.015420	1.502486	-0.000220	0.016210	0.000244
1.632462	0.016456	1.632200	0.000262	0.016515	0.000270
1.702568	0.017019	1.702653	-0.000085	0.016715	0.000285
1.832765	0.018058	1.832686	0.000079	0.017145	0.000314
1.902870	0.018615	1.902446	0.000425	0.017411	0.000331
2.003021	0.019422	2.003529	-0.000507	0.017754	0.000356

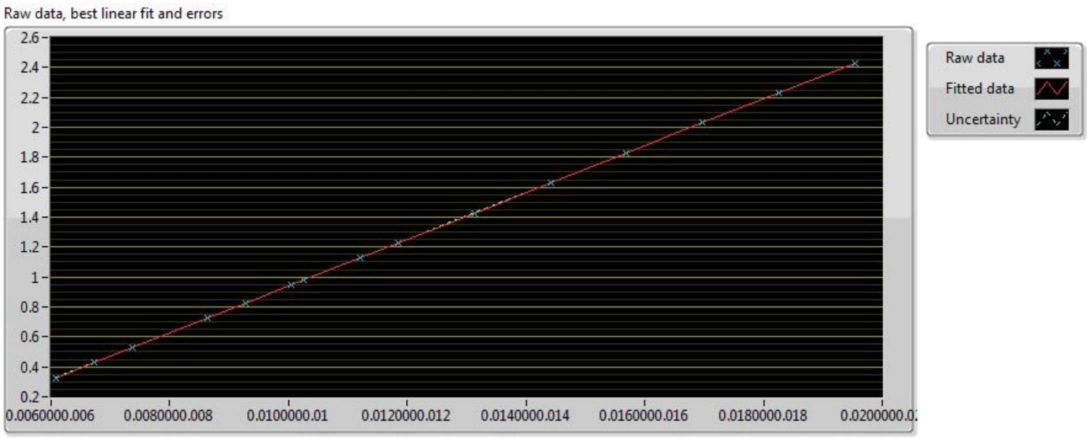
Calibration report

Calibration properties
Calibrated by: Sigrid Marie Skodje
Type/producer: PTX 610
SN: 2480173
Range: 2.5bar a
Unit: Bar

Calibrator properties
Type/producer: GE sensing Pressurements deadweight tester P3023-6-P
SN: 66611
Uncertainty: 0.008%

Calibration summary
Max Uncertainty: 0.000294[%]
Max uncertainty: 0.056319[bar]
Calibration points: 15.000000

Linear fit eqation
Y=156.167608x+-0.621796



Logged calibration points

Pressure	Ampere	Best linear fit	Deviation	Uncertainty %	Uncertainty
0.327093	0.006078	0.327352	-0.000258	0.056319	0.000184
0.427244	0.006716	0.427060	0.000184	0.040400	0.000173
0.527396	0.007359	0.527433	-0.000037	0.030826	0.000163
0.727698	0.008640	0.727565	0.000133	0.020300	0.000148
0.827849	0.009284	0.828105	-0.000256	0.017257	0.000143
0.948030	0.010050	0.947660	0.000370	0.014669	0.000139
0.978075	0.010245	0.978185	-0.000110	0.014280	0.000140
1.128302	0.011206	1.128172	0.000130	0.012675	0.000143
1.228453	0.011850	1.228732	-0.000279	0.011900	0.000146
1.428755	0.013130	1.428618	0.000138	0.011152	0.000159
1.629057	0.014413	1.629005	0.000052	0.010974	0.000179
1.829359	0.015696	1.829429	-0.000070	0.011141	0.000204

2029662	0.016978	2.029571	0.000090	0.011475	0.000233
2.229964	0.018260	2.229807	0.000157	0.011777	0.000263
2.430266	0.019545	2.430510	-0.000244	0.012104	0.000294

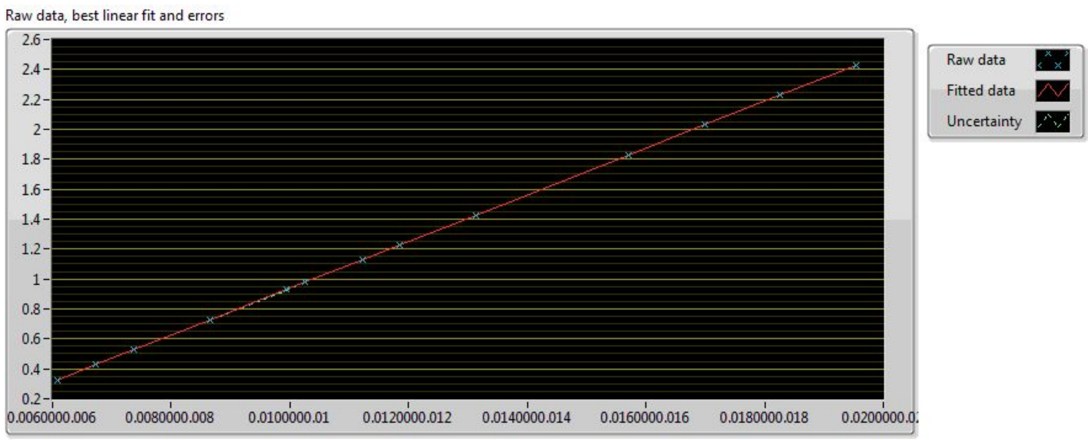
Calibration report

Calibration properties
Calibrated by: Sigrid Marie Skodje
Type/producer: PTX 610
SN: 2738458
Range: 2.5bar a
Unit: Bar

Calibrator properties
Type/producer: GE sensing Pressurements deadweight tester P3023-6-P
SN: 66611
Uncertainty: 0.008%

Calibration summary
Max Uncertainty: 0.000346[%]
Max uncertainty: 0.073927[bar]
Calibration points: 13.000000

Linear fit eqation
Y=156.237595x+-0.624527



logged calibration points

Pressure	Ampere	Best linear fit	Deviation	Uncertainty %	Uncertainty
0.326693	0.006087	0.326463	0.000230	0.073927	0.000242
0.426844	0.006729	0.426743	0.000101	0.052970	0.000226
0.526995	0.007369	0.526795	0.000200	0.040168	0.000212
0.727297	0.008653	0.727440	-0.000143	0.025996	0.000189
0.927599	0.009934	0.927552	0.000047	0.018743	0.000174
0.977675	0.010254	0.977602	0.000072	0.017550	0.000172
1.127901	0.011218	1.128182	-0.000281	0.015113	0.000170
1.228052	0.011859	1.228228	-0.000175	0.014198	0.000174
1.428355	0.013141	1.428513	-0.000158	0.013013	0.000186
1.828959	0.015706	1.829344	-0.000385	0.013003	0.000238
2.029261	0.016986	2.029357	-0.000096	0.013389	0.000272
2.229563	0.018267	2.229539	0.000025	0.013798	0.000308
2.429865	0.019546	2.429302	0.000564	0.014239	0.000346

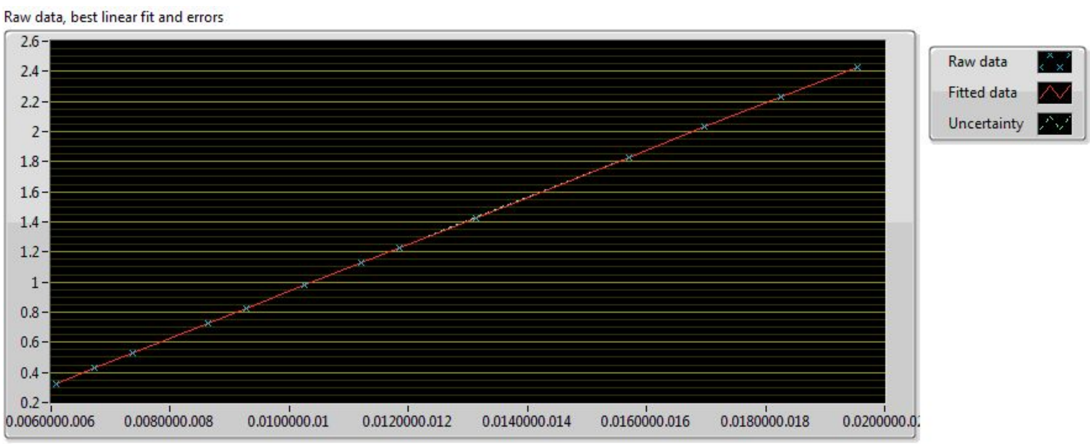
Calibration report

Calibration properties
Calibrated by: Sigrid Marie Skodje
Type/producer: PTX 610
SN: 2738456
Range: 2.5bar a
Unit: Bar

Calibrator properties
Type/producer: GE sensing Pressurements deadweight tester P3023-6-P
SN: 66611
Uncertainty: 0.008%

Calibration summary
Max Uncertainty: 0.000420[bar]
Max uncertainty: 0.094633[%]
Calibration points: 13

Linear fit eqation
Y=156.244957x-0.623428



Logged calibration points

Pressure	Ampere	Best linear fit	Deviation	Uncertainty %	Uncertainty
0.326492	0.006077	0.326096	0.000397	0.094633	0.000309
0.426644	0.006719	0.426420	0.000224	0.067596	0.000288
0.526795	0.007361	0.526677	0.000118	0.051218	0.000270
0.727097	0.008644	0.727091	0.000006	0.032614	0.000237
0.827248	0.009284	0.827207	0.000041	0.027302	0.000226
0.977474	0.010246	0.977492	-0.000018	0.021701	0.000212
1.127701	0.011210	1.128112	-0.000411	0.018505	0.000209
1.227852	0.011851	1.228190	-0.000338	0.016956	0.000208
1.428154	0.013133	1.428566	-0.000412	0.015542	0.000222
1.828759	0.015697	1.829113	-0.000354	0.015582	0.000285
2.029061	0.016977	2.029192	-0.000131	0.016049	0.000326
2.229363	0.018257	2.229068	0.000295	0.016624	0.000371
2.429665	0.019537	2.429083	0.000582	0.017274	0.000420

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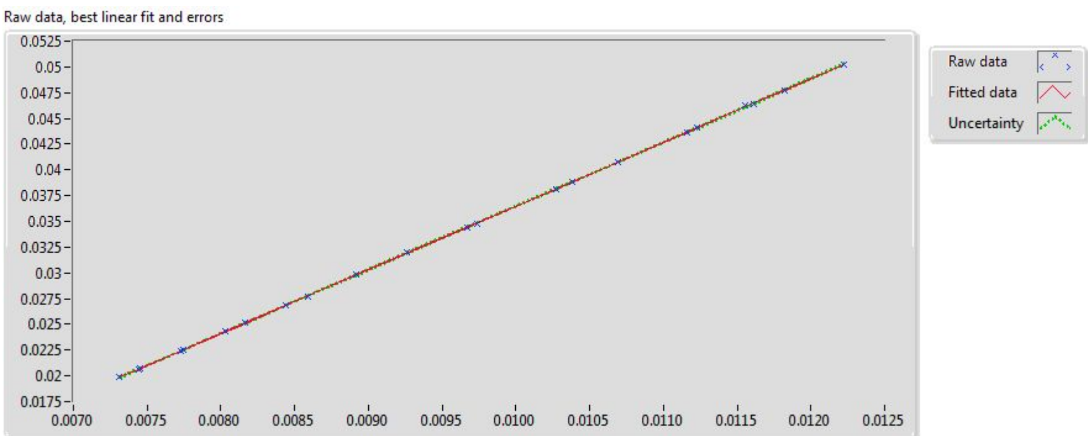
Calibration report

Calibration properties
Calibrated by: Sigrid Marie Skodje
Type/producer: Optiflux 2300 C
SN: A07 00871
Range:
Unit: m3/s

Calibrator properties
Type/producer: Optiflux 2000 F
SN: A05 1090
Uncertainty: %

Calibration summary
Max Uncertainty: 0.000043[bar]
Max uncertainty: 0.189443[%]
Calibration points: 22.000000

Linear fit eqation
Y=6.187273x-0.025382



Logged calibration points

Pressure	Ampere	Best linear fit	Deviation	Uncertainty %	Uncertainty
0.020705	0.007454	0.020739	-0.000034	0.173852	0.000036
0.022465	0.007726	0.022422	0.000043	0.147380	0.000033
0.025135	0.008160	0.025104	0.000032	0.115140	0.000029
0.026826	0.008439	0.026831	-0.000005	0.099223	0.000027
0.029883	0.008919	0.029800	0.000083	0.078709	0.000024
0.034802	0.009740	0.034884	-0.000082	0.063791	0.000022
0.038169	0.010270	0.038160	0.000008	0.063705	0.000024
0.040699	0.010691	0.040767	-0.000068	0.067175	0.000027
0.044097	0.011224	0.044065	0.000032	0.073234	0.000032
0.046394	0.011613	0.046470	-0.000077	0.078284	0.000036
0.047745	0.011821	0.047755	-0.000010	0.080977	0.000039
0.050251	0.012224	0.050252	-0.000001	0.086214	0.000043
0.046242	0.011555	0.046109	0.000134	0.077157	0.000036
0.043659	0.011161	0.043676	-0.000017	0.072345	0.000032
0.038863	0.010384	0.038868	-0.000005	0.064475	0.000025
0.034456	0.009670	0.034447	0.000009	0.064401	0.000022
0.031964	0.009262	0.031927	0.000037	0.069712	0.000022
0.027730	0.008593	0.027788	-0.000058	0.091724	0.000025
0.024296	0.008032	0.024316	-0.000020	0.123786	0.000030
0.022581	0.007747	0.022551	0.000029	0.145693	0.000033
0.020609	0.007440	0.020649	-0.000040	0.175560	0.000036
0.019850	0.007309	0.019838	0.000012	0.189443	0.000038

The uncertainty is calculated with 95% confdence.

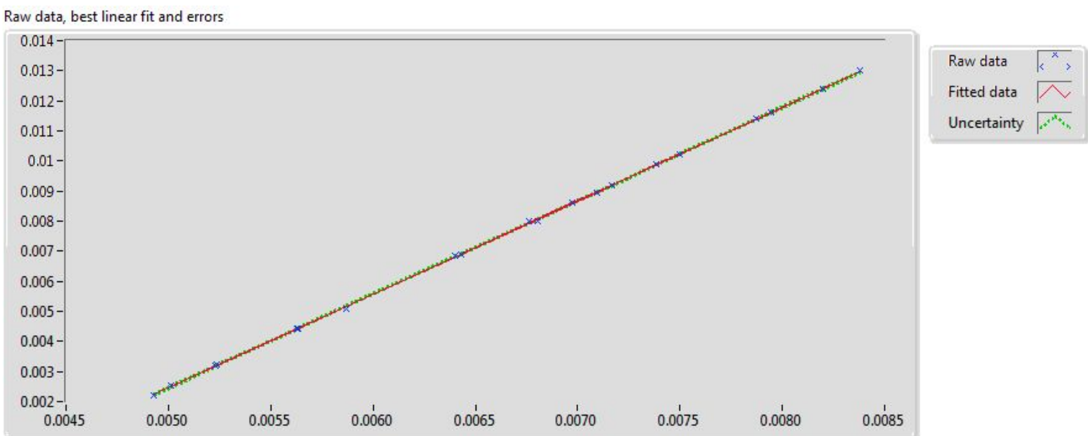
Calibration report

Calibration properties
Calibrated by: Sigrid Marie Skodje
Type/producer: Optiflux 2300 C
SN: A07 00945
Range:
Unit: m3/s

Calibrator properties
Type/producer: Optiflux 2000 F
SN: A05 1090
Uncertainty: %

Calibration summary
Max Uncertainty: 0.000031[bar]
Max uncertainty: 1.372417[%]
Calibration points: 20.000000

Linear fit eqation
Y=3.107779x-0.013078



Logged calibration points

Pressure	Ampere	Best linear fit	Deviation	Uncertainty %	Uncertainty
0.002215	0.004927	0.002234	-0.000019	1.372417	0.000030
0.003232	0.005239	0.003203	0.000029	0.820373	0.000027
0.004437	0.005633	0.004427	0.000010	0.498035	0.000022
0.005085	0.005872	0.005172	-0.000087	0.389596	0.000020
0.006857	0.006400	0.006813	0.000044	0.241528	0.000017
0.008015	0.006807	0.008076	-0.000061	0.205312	0.000016
0.008603	0.006976	0.008601	0.000001	0.198522	0.000017
0.009195	0.007165	0.009188	0.000007	0.197736	0.000018
0.010204	0.007501	0.010234	-0.000029	0.205664	0.000021
0.011609	0.007945	0.011613	-0.000004	0.222146	0.000026
0.013009	0.008379	0.012961	0.000048	0.239791	0.000031
0.012378	0.008200	0.012404	-0.000026	0.233461	0.000029
0.011412	0.007870	0.011380	0.000032	0.218383	0.000025
0.009876	0.007385	0.009874	0.000002	0.201940	0.000020
0.008928	0.007092	0.008961	-0.000033	0.198349	0.000018
0.007983	0.006762	0.007936	0.000047	0.204874	0.000016
0.006894	0.006429	0.006901	-0.000008	0.239037	0.000016
0.004412	0.005631	0.004422	-0.000010	0.501268	0.000022
0.003202	0.005231	0.003179	0.000023	0.831048	0.000027
0.002527	0.005010	0.002493	0.000034	1.160985	0.000029

The uncertainty is calculated with 95% confdence.

Appendix C

Safe job analysis

NTNU SINTEF

Risikovurderingsrapport

Swirlrigg

Prosjekttittel	Swirlrigg
Prosjektleder	Torbjørn Nielsen
Enhet	NTNU
HMS-koordinator	**Morten Grønli**
Linjeleder	Olav Bolland
Plassering	Vannkraftlaboratoriet, 2.etasje
Romnummer	
Riggansvarlig	Sigrid Marie Skodje (student)
Risikovurdering utført av	Sigrid Marie Skodje

Godkjenning:

	Navn	Dato	Sign
Prosjektleder	Torbjørn K. Nielsen	6/5 - 13	[signature]
HMS koordinator	PER BJØRNAAS	6/5 - 13	[signature]
Linjeleder	OLAV BOLLAND	6/5 - 13	[signature]

INNHOLDSFORTEGNELSE

1 INNLEDNING

Eksisterende swirlrigg plassert i 2. etasje på Vannkraftlaboratoriet. Riggen skal kjøres med 3 trykksensorer, 3 differentialtrykk-sensorer og 4 flowmeter. Målingene skal registreres av en RIO. Formålet er å verifisere et LabView sanntids programvare for modellering, måling og kontroll.

2 KONKLUSJON

Riggen er bygget til god laboratorium praksis (GLP).

Apparaturkortet får en gyldighet på **12 måneder**
Forsøk pågår kort får en gyldighet på **12 måneder**

3 ORGANISERING

Rolle	NTNU
Prosjektleder	Torbjørn Nielsen
Apparaturansvarlig	Bård Brandåstrø
Romansvarlig	
HMS koordinator	Morten Grønli
HMS ansvarlig (linjeleder):	Olav Bolland

4 RISIKOSTYRING AV PROSJEKTET

Hovedaktiviteter risikostyring	Nødvendige tiltak, dokumentasjon	DTG
Prosjekt initiering	Prosjekt initiering mal	
Veiledningsmøte	Skjema for Veiledningsmøte med pre-risikovurdering	
Innledende risikovurdering	Fareidentifikasjon – HAZID Skjema grovanalyse	
Vurdering av teknisk sikkerhet	Prosess-HAZOP Tekniske dokumentasjoner	
Vurdering av operasjonell sikkerhet	Prosedyre-HAZOP Opplæringsplan for operatører	
Sluttvurdering, kvalitetssikring	Uavhengig kontroll Utstedelse av apparaturkort Utstedelse av forsøk pågår kort	

5 TEGNINGER, FOTO, BESKRIVELSER AV FORSØKSOPPSETT

Vedlegg:
Prosess og Instrumenterings Diagram, (PID) skal inneholde:

- *Alle komponenter i forsøksoppsetningen*
- *Komponentliste med spesifikasjoner*

- *Tegninger og bilder som beskriver forsøksoppsetningen.*

Hvor oppholder operatør seg, hvor er gassflasker, avstegningsventiler for vann/luft.
Annen dokumentasjon som beskriver oppsett og virkemåte.

6 EVAKUERING FRA FORSØKSOPPSETNINGEN

Evakuering skjer på signal fra alarmklokker eller lokale gassalarmstasjon med egen lokal varsling med lyd og lys utenfor aktuelle rom, se 6.2
Evakuering fra rigg området foregår igjennom merkede nødutganger til møteplass, (hjørnet gamle kjemi/kjelhuset eller parkeringsplass 1a-b.)
Aksjon på rigg ved evakuering: *Pumpen til riggen skal være avslått.*

7 VARSLING

7.1 Før forsøkskjøring

Varsling per e-post, til **Liste iept-experiments@ivt.ntnu.no**
I e-posten skal det stå::

- Navn på forsøksleder:
- Navn på forsøksrigg:
- Tid for start: (dato og klokkelslett)
- Tid for stop: (dato og klokkelslett)

All forsøkskjøringen skal planlegges og legges inn i aktivitetskalender for lab. Forsøksleder må få bekreftelse på at forsøkene er klarert med øvrig labdrift før forsøk kan iverksettes.

7.2 Ved uønskede hendelser

BRANN
Ved brann en ikke selv er i stand til å slukke med rimelige lokalt tilgjengelige slukkemidler, skal nærmeste brannalarm utløses og arealet evakueres raskest mulig. En skal så være tilgjengelig for brannvesen/bygningsvaktmester for å påvise brannsted.
Om mulig varsles så:

NTNU	SINTEF
Morten Grønli, Mob: 918 97 515	Harald Mæhlum, Mob: 930 14 986
Olav Bolland: Mob: 918 97 209	Anne Karin T. Hemmingsen Mob: 930 19 669
NTNU – SINTEF Beredskapstelefon	800 80 388

GASSALARM
Ved gassalarm skal gassflasker stenges umiddelbart og området ventileres. Klarer man ikke innen rimelig tid å få ned nivået på gasskonsentrasjonen så utløses brannalarm og laben evakueres. Dedikert personell og eller brannvesen sjekker så lekkasjested for å fastslå om det er mulig å tette lekkasje og lufte ut området på en forsvarlig måte.
Varslingsrekkefølge som i overstående punkt.

PERSONSKADE

- Førstehjelpsutstyr i Brann/førstehjelpsstasjoner,

- Rop på hjelp,
- Start livreddende førstehjelp
- **Ring 113** hvis det er eller det er tvil om det er alvorlig skade.

ANDRE UØNSKEDE HENDELSER (AVVIK)
NTNU:
Rapportering av uønskede hendelser, Innsida, avviksmeldinger
https://innsida.ntnu.no/wiki/-/wiki/Norsk/Melde+avvik

SINTEF:
Synergi

8 VURDERING AV TEKNISK SIKKERHET

8.1 Fareidentifikasjon, HAZOP

Se kapittel 13 "Veiledning til rapport mal.
Forsøksoppsetningen deles inn i følgende noder:

Node 1	Pumpe til rigg	
Node 2	Testrigg	
Node 3	Sump	

Vedlegg, skjema: Hazop_mal
Vurdering: (Sikkerhet ivaretatt)

8.2 Brannfarlig, reaksjonsfarlig og trykksatt stoff og gass

Se kapittel 13 "Veiledning til rapport mal.
Inneholder forsøkene brannfarlig, reaksjonsfarlig og trykksatt stoff

JA	Eksplosjonsverndokument utarbeides og eller dokumentert trykktest, (kap 7.3)

Vurdering: *Vann ved lavt trykk*

8.3 Trykkpåkjent utstyr

Inneholder forsøksoppsetningen trykkpåkjent utstyr:

JA	

Vurdering: Eksisterende rigg

8.4 Påvirkning av ytre miljø (utslipp til luft/vann, støy, temperatur, rystelser, lukt)

Se kapittel 13 "Veiledning til rapport mal..

NEI	

8.5 Stråling

Se kapittel 13 "Veiledning til rapport mal.

NEI	

8.6 Bruk og behandling av kjemikalier

NEI	

8.7 El sikkerhet (behov for å avvike fra gjeldende forskrifter og normer)

NEI	

9 VURDERING AV OPERASJONELL SIKKERHET

Sikrer at etablerte prosedyrer dekker alle identifiserte risikoforhold som må håndteres gjennom operasjonelle barrierer og at operatører og teknisk utførende har tilstrekkelig kompetanse.

9.1 Prosedyre HAZOP

Se kapittel 13 "Veiledning til rapport mal.
Metoden er en undersøkelse av operasjonsprosedyrer, og identifiserer årsaker og farekilder for operasjonelle problemer.
Vedlegg: HAZOP_MAL_Prosedyre
Vurdering:

9.2 Drifts og nødstopps prosedyre

Se kapittel 13 "Veiledning til rapport mal.
Driftsprosedyren er en sjekkliste som skal fylles ut for hvert forsøk.
Nødstopp prosedyren skal sette forsøksoppsetningen i en harmløs tilstand ved uforutsette hendelser.

Vedlegg Prosedyre for drift av swirlrigg
Nødstopp prosedyre: Pumpa til rigg stoppes ved å trykke på nødstoppsbryter enten på østveggen ved peltonturbin eller inne i kontrollbua.

9.3 Opplæring av operatører

Dokument som viser Opplæringsplan for operatører utarbeides for alle forøksoppsetninger.

- *Hvilke krav er det til opplæring av operatører.*
- *Hva skal til for å bli selvstendig operatør*
- *Arbeidsbeskrivelse for operatører*

Vedlegg: Opplæringsplan for operatører

9.4 Tekniske modifikasjoner

9.5 Personlig verneutstyr

- *Det er påbudt med vernebriller i sonen anlegget er plassert i.*
- *Det skal benyttes hørselsvern ved drift av rigg.*

9.6 Generelt

- *Vann og trykklufttilførsel i slanger skal stenges/kobles fra ved nærmeste fastpunkt når riggen ikke er i bruk.*

9.7 Sikkerhetsutrustning

9.8 Spesielle tiltak

10 TALLFESTING AV RESTRISIKO – RISIKOMATRISE

Se kapittel 13 "Veiledning til rapport mal.
Risikomatrisen vil gi en visualisering og en samlet oversikt over aktivitetens risikoforhold slik at ledelse og brukere får et mest mulig komplett bilde av risikoforhold.

IDnr	Aktivitet-hendelse	Frekv-Sans	Kons	RV
	Ledningsbrudd Vannsprut med lavt trykk *Vernebriller skal benyttes*	1	B	B1
	Støy ved drift *Hørselsvern skal benyttes*	4	B	B4
	Feil bruk av utstyr, skade på utstyr *Driftsprosedyre skal følges*	1	C	C1

Vurdering restrisiko: *Deltakerne foretar en helhetsvurdering for å avgjøre om gjenværende risiko ved aktiviteten/prosessen er akseptabel. Avsperring og kjøring utenom arbeidstid*

11 LOVER FORSKRIFTER OG PÅLEGG SOM GJELDER

Se http://www.arbeidstilsynet.no/regelverk/index.html

- Lov om tilsyn med elektriske anlegg og elektrisk utstyr (1929)
- Arbeidsmiljøloven
- Forskrift om systematisk helse-, miljø- og sikkerhetsarbeid (HMS Internkontrollforskrift)
- Forskrift om sikkerhet ved arbeid og drift av elektriske anlegg (FSE 2006)
- Forskrift om elektriske forsyningsanlegg (FEF 2006)
- Forskrift om utstyr og sikkerhetssystem til bruk i eksplosjonsfarlig område NEK 420
- Forskrift om håndtering av brannfarlig, reaksjonsfarlig og trykksatt stoff samt utstyr og anlegg som benyttes ved håndteringen
- Forskrift om Håndtering av eksplosjonsfarlig stoff
- Forskrift om bruk av arbeidsutstyr.
- Forskrift om Arbeidsplasser og arbeidslokaler
- Forskrift om Bruk av personlig verneutstyr på arbeidsplassen
- Forskrift om Helse og sikkerhet i eksplosjonsfarlige atmosfærer
- Forskrift om Høytrykksspyling
- Forskrift om Maskiner
- Forskrift om Sikkerhetsskilting og signalgivning på arbeidsplassen
- Forskrift om Stillaser, stiger og arbeid på tak m.m.
- Forskrift om Sveising, termisk skjæring, termisk sprøyting, kullbuemeisling, lodding og sliping (varmt arbeid)
- Forskrift om Tekniske innretninger
- Forskrift om Tungt og ensformig arbeid
- Forskrift om Vern mot eksponering for kjemikalier på arbeidsplassen (Kjemikalieforskriften)
- Forskrift om Vern mot kunstig optisk stråling på arbeidsplassen
- Forskrift om Vern mot mekaniske vibrasjoner
- Forskrift om Vern mot støy på arbeidsplassen

Veiledninger fra arbeidstilsynet
se: http://www.arbeidstilsynet.no/regelverk/veiledninger.html

12 DOKUMENTASJON

- Tegninger, foto, beskrivelser av forsøksoppsetningen
- Hazop_mal
- Sertifikat for trykkpåkjent utstyr
- Håndtering avfall i NTNU
- Sikker bruk av LASERE, retningslinje
- HAZOP_MAL_Prosedyre
- Forsøksprosedyre
- Opplæringsplan for operatører
- Skjema for sikker jobb analyse, (SJA)
- Apparaturkortet
- Forsøk pågår kort

13 VEILEDNING TIL RAPPORTMAL

Kapittel 7 Vurdering av teknisk sikkerhet

Sikre at design av apparatur er optimalisert i forhold til teknisk sikkerhet.
Identifisere risikoforhold knyttet til valgt design, og eventuelt å initiere re-design for å sikre at størst mulig andel av risiko elimineres gjennom teknisk sikkerhet.
Punktene skal beskrive hva forsøksoppsetningen faktisk er i stand til å tåle og aksept for utslipp.

7.1 Fareidentifikasjon, HAZOP

Forsøksoppsetningen deles inn i noder: (eks *Motorenhet, pumpeenhet, kjøleenhet.)*
Ved hjelp av ledeord identifiseres årsak, konsekvens og sikkerhetstiltak. Konkluderes det med at tiltak er nødvendig anbefales disse på bakgrunn av dette. Tiltakene lukkes når de er utført og Hazop sluttføres.
(eks "No flow", årsak: rør er deformert, konsekvens: pumpe går varm, sikkerhetsforanstaltning: måling av flow med kobling opp mot nødstopp eller hvis konsekvensen ikke er kritisk benyttes manuell overvåkning og punktet legges inn i den operasjonelle prosedyren.)

7.2 Brannfarlig, reaksjonsfarlig og trykksatt stoff.

I henhold til Forskrift om håndtering av brannfarlig, reaksjonsfarlig og trykksatt stoff samt utstyr og anlegg som benyttes ved håndteringen

Brannfarlig stoff: Fast, flytende eller gassformig stoff, stoffblanding, samt stoff som forekommer i kombinasjoner av slike tilstander, som i kraft av sitt flammepunkt, kontakt med andre stoffer, trykk, temperatur eller andre kjemiske egenskaper representerer en fare for brann.
Reaksjonsfarlig stoff: Fast, flytende, eller gassformig stoff, stoffblanding, samt stoff som forekommer i kombinasjoner av slike tilstander, som ved kontakt med vann, ved sitt trykk, temperatur eller andre kjemiske forhold, representerer en fare for farlig reaksjon, eksplosjon eller utslipp av farlig gass, damp, støv eller tåke.
Trykksatt stoff: Annet fast, flytende eller gassformig stoff eller stoffblanding enn brann- eller reaksjonsfarlig stoff, som er under trykk, og som derved kan representere en fare ved ukontrollert utslipp.

Nærmere kriterier for klassifisering av brannfarlig, reaksjonsfarlig og trykksatt stoff er fastsatt i vedlegg 1 i veiledningen til forskriften "Brannfarlig, reaksjonsfarlig og trykksatt stoff"
http://www.dsb.no/Global/Publikasjoner/2009/Veiledning/Generell%20veiledning.pdf
http://www.dsb.no/Global/Publikasjoner/2010/Tema/Temaveiledning_bruk_av_farlig_stoff_Del_1.pdf
Rigg og areal skal gjennomgås med hensyn på vurdering av Ex sone

- Sone 0: Alltid eksplosiv atmosfære, for eksempel inne i tanker med gass, brennbar væske.
- Sone 1: Primær sone, tidvis eksplosiv atmosfære for eksempel et fylle tappe punkt

- Sone 2: Sekundert utslippssted, kan få eksplosiv atmosfære ved uhell, for eksempel ved flenser, ventiler og koblingspunkt

7.4 Påvirkning av ytre miljø

Med forurensning forstås: tilførsel av fast stoff, væske eller gass til luft, vann eller i grunnen støy og rystelser påvirkning av temperaturen som er eller kan være til skade eller ulempe for miljøet.
Regelverk: http://www.lovdata.no/all/hl-19810313-006.html#6
NTNU retningslinjer for avfall se: http://www.ntnu.no/hms/retningslinjer/HMSR18B.pdf

7.5 Stråling

Stråling defineres som

Ioniserende stråling: Elektromagnetisk stråling (i strålevernsammenheng med bølgelengde <100 nm) eller hurtige atomære partikler (f.eks alfa- og beta-partikler) som har evne til å ionisere atomer eller molekyler
Ikke-ioniserende stråling: Elektromagnetisk stråling (bølgelengde >100 nm), og ultralyd[1], som har liten eller ingen evne til å ionisere.
Strålekilder: Alle ioniserende og sterke ikke-ioniserende strålekilder.
Ioniserende strålekilder: Kilder som avgir ioniserende stråling, f.eks alle typer radioaktive kilder, røntgenapparater, elektronmikroskop
Sterke ikke-ioniserende strålekilder: Kilder som avgir sterk ikke-ioniserende stråling som kan skade helse og/eller ytre miljø, f.eks laser klasse 3B og 4, MR[2]-systemer, UVC[3]-kilder, kraftige IR-kilder[4]
1 Ultralyd er akustisk stråling ("lyd") over det hørbare frekvensområdet (>20 kHz). I strålevernforskriften er ultralyd omtalt sammen med elektromagnetisk ikke-ioniserende stråling. 2 MR (eg. NMR) - kjernemagnetisk resonans, metode som nyttes til å «avbilde» indre strukturer i ulike materialer. 3 UVC er elektromagnetisk stråling i bølgelengdeområdet 100-280 nm. 4 IR er elektromagnetisk stråling i bølgelengdeområdet 700 nm – 1 mm.

For hver laser skal det finnes en informasjonsperm(HMSRV3404B) som skal inneholde:

- Generell informasjon
- Navn på instrumentansvarlig og stedfortreder, og lokal strålevernskoordinator
- Sentrale data om apparaturen
- Instrumentspesifikk dokumentasjon
- Referanser til (evt kopier av) datablader, strålevernbestemmelser, o.l.
- Vurderinger av risikomomenter
- Instruks for brukere
- Instruks for praktisk bruk; oppstart, drift, avstenging, sikkerhetsforholdsregler, loggføring, avlåsing, evt. bruk av strålingsmåler, osv.
- Nødprosedyrer

Se ellers retningslinjen til NTNU for laser: http://www.ntnu.no/hms/retningslinjer/HMSR34B.pdf

7.6 Bruk og behandling av kjemikalier.

Her forstås kjemikalier som grunnstoff som kan utgjøre en fare for arbeidstakers sikkerhet og helse.
Se ellers: http://www.lovdata.no/cgi-wift/ldles?doc=/sf/sf/sf-20010430-0443.html
Sikkerhetsdatablar skal være i forøkenes HMS perm og kjemikaliene registrert i Stoffkartoteket.

Kapittel 8 Vurdering av operasjonell sikkerhet

Sikrer at etablerte prosedyrer dekker alle identifiserte risikoforhold som må håndteres gjennom operasjonelle barrierer og at operatører og teknisk utførende har tilstrekkelig kompetanse.

8.1 Prosedyre Hazop

Prosedyre-HAZOP gjennomføres som en systematisk gjennomgang av den aktuelle prosedyren ved hjelp av fastlagt HAZOP-metodikk og definerte ledeord. Prosedyren brytes ned i enkeltstående arbeidsoperasjoner (noder) og analyseres ved hjelp av ledeordene for å avdekke mulige avvik, uklarheter eller kilder til mangelfull gjennomføring og feil.

8.2 Drifts og nødstopp prosedyrer

Utarbeides for alle forsøksoppsetninger.
Driftsprosedyren skal stegvis beskrive gjennomføringen av et forsøk, inndelt i oppstart, under drift og avslutning. Prosedyren skal beskrive forutsetninger og tilstand for start, driftsparametere med hvor store avvik som tillates før forsøket avbrytes og hvilken tilstand riggen skal forlates.
Nødstopp-prosedyre beskriver hvordan en nødstopp skal skje, (utført av uinnvidde),
hva som skjer, (strøm/gass tilførsel) og
hvilke hendelser som skal aktivere nødstopp, (brannalarm, lekkasje).

Kapittel 9 Risikomatrise Tallfesting av restrisiko

For å synliggjøre samlet risiko, jevnfør skjema for risikovurdering, plottes hver enkelt aktivitets verdi for sannsynlighet og konsekvens inn i risikomatrisen. Bruk aktivitetens IDnr. Eksempel: Hvis aktivitet med IDnr. 1 har fått en risikoverdi D3 (sannsynlighet 3 x konsekvens D) settes aktivitetens IDnr i risikomatrisens felt for 3D. Slik settes alle aktivitetenes risikoverdier (IDnr) inn i risikomatrisen.
I risikomatrisen er ulike grader av risiko merket med rød, gul eller grønn. Når en aktivitets risiko havner på rød (= uakseptabel risiko), skal risikoreduserende tiltak gjennomføres. Ny vurdering gjennomføres etter at tiltak er iverksatt for å se om risikoverdien er kommet ned på akseptabelt nivå.

KONSEKVENS	Svært alvorlig	E1	E2	E3	E4	E5
	Alvorlig	D1	D2	D3	D4	D5
	Moderat	C1	C2	C3	C4	C5
	Liten	B1	B2	B3	B4	B5
	Svært liten	A1	A2	A3	A4	A5
		Svært liten	Liten	Middels	Stor	Svært Stor
		SANSYNLIGHET				

Prinsipp over akseptkriterium. Forklaring av fargene som er brukt i risikomatrisen.

Farge		Beskrivelse
Rød		Uakseptabel risiko. Tiltak skal gjennomføres for å redusere risikoen.
Gul		Vurderingsområde. Tiltak skal vurderes.
Grønn		Akseptabel risiko. Tiltak kan vurderes ut fra andre hensyn.

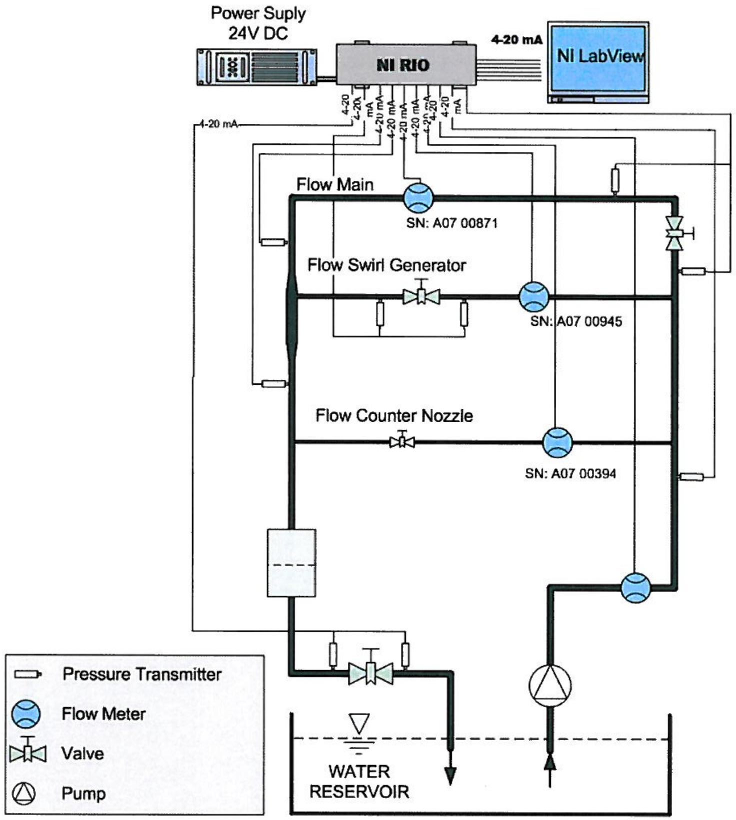
Vedlegg til Risikovurderingsrapport

SWIRL-rigg

Prosjekttittel	SWIRL-rigg
Apparatur	SWIRL-rigg
Enhet	NTNU
Apparaturansvarlig	Bård Brandåstrø
Prosjektleder	Torbjørn Nielsen
HMS-koordinator	Morten Grønli
HMS-ansvarlig (linjeleder)	Olav Bolland
Plassering	Vannkraftlaboratoriet, 2.etasje
Romnummer	21
Risikovurdering utført av	Sigrid Marie Skodje i samarbeid med Bård Brandåstrø

INNHOLDSFORTEGNELSE

VEDLEGG A: PROSESS OG INSTRUMENTERINGSDIAGRAM



VEDLEGG B: PROSESS OGHAZOP MAL

Project: Node: 1						Page	
Ref#	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
	No flow						
	Reverse flow						
	More flow						
	Less flow						
	More level						
	Less level						
	More pressure						
	Less pressure						
	More temperature						
	Less temperature						
	More viscosity						
	Less viscosity						
	Composition Change						
	Contamination						
	Relief						
	Instrumentation						
	Sampling						
	Corrosion/erosion						
	Service failure						
	Abnormal operation						
	Maintenance						

Project:
Node: 1

Page

Ref#	Guideword	Causes	Consequences	Safeguards	Recommendations	Action	Date/Sign
	Ignition						
	Spare equipment						
	Safety						

VEDLEGG C: PRØVESERTIFIKAT FOR LOKAL TRYKKTESTING

Trykk testen skal utføres I følge NS-EN 13445 del 5 (Inspeksjon og prøving).
Se også prosedyre for trykktesting gjeldende for VATL lab

Trykkpåkjent utstyr:	
Benyttes i rigg:	
Design trykk for utstyr (bara):	
Maksimum tillatt trykk (bara): (i.e. burst pressure om kjent)	
Maksimum driftstrykk i denne rigg:	

Prøvetrykket skal fastlegges i følge standarden og med hensyn til maksimum tillatt trykk.

Prøvetrykk (bara):			
X maksimum driftstrykk: I følge standard			
Test medium:			
Temperatur (°C)			
Start tid:		Trykk (bara):	
Slutt tid:		Trykk (bara):	
Maksimum driftstrykk i denne rigg:			

Eventuelle repetisjoner fra atm. trykk til maksimum prøvetrykk:................

Test trykket, dato for testing og maksimum tillatt driftstrykk skal markers på (skilt eller innslått)

Sted og dato

Signatur

VEDLEGG D: HAZOP MAL PROSEDYRE

Project: Node: 1						Page	
Ref#	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
	Uklar	Prosedyre er laget for ambisiøs eller preget av forvirring					
	Trinn på feil plass	Prosedyren vil lede til at handlinger blir gjennomført i feil mønster/rekkefølge					
	Feil handling	Prosedyrens handling er feil spesifisert					
	Uriktig informasjon	Informasjon som er gitt i forkant av handling er feil spesifisert					
	Trinn utelatt	Manglende trinn, eller trinn krever for mye av operatør					
	Trinn mislykket	Trinn har stor sannsynlighet for å mislykkes					
	Påvirkning og effekter fra andre	Prosedyrens prestasjoner vil trolig bli påvirket av andre kilder					

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VEDLEGG G: FORSØKSPROSEDYRE

Experiment, name, number: **Swirl rig**	**Date/** 06.05.2013 **Sign**
Project Leader: **Torbjørn Nielsen**	[signature]
Experiment Leader: **Sigrid Marie Skodje**	Sigrid M. Skodje
Operator, Duties: Sigrid M. Skodje	Sigrid M. Skodje

	Conditions for the experiment:	**Completed**
	Experiments should be run in normal working hours, 08:00-16:00 during winter time and 08.00-15.00 during summer time. Experiments outside normal working hours shall be approved.	ok SMS
	One person must always be present while running experiments, and should be approved as an experimental leader.	ok SMS
	An early warning is given according to the lab rules, and accepted by authorized personnel.	ok SMS
	Be sure that everyone taking part of the experiment is wearing the necessary protecting equipment and is aware of the shut down procedure and escape routes.	ok SMS
	Preparations	**Carried out**
	Post the "Experiment in progress" sign.	SMS
	Start up procedure	**Ved kjøring**
	During the experiment	
	Control of temperature, pressure	SMS
	End of experiment	
	Shut down procedure	SMS
	Remove all obstructions/barriers/signs around the experiment.	✓
	Tidy up and return all tools and equipment.	✓
	Tidy and cleanup work areas.	✓
	Return equipment and systems back to their normal operation settings (fire alarm)	✓
	To reflect on before the next experiment and experience useful for others	
	Was the experiment completed as planned and on scheduled in professional terms?	
	Was the competence which was needed for security and completion of the experiment available to you?	
	Do you have any information/ knowledge from the experiment that you should document and share with fellow colleagues?	

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VEDLEGG H: OPPLÆRINGSPLAN FOR OPPERATØRER

Experiment, name, number: **Swirl rig**	
Project Leader: **Torbjørn Nielsen**	**Date/Sign**
Operator Sigrid Marie Skoadje	Sigrid M. Skoadje

	Gjennomført HMS kurs for EPT lab	OK SMS
	Runde i lab	OK SMS
	Rutiner/regler og Arbeidstid	OK SMS
	Kjenner til evakueringsprosedyrer	OK SMS
	Aktivitetskalender	OK SMS
	Innmelding av forsøk til: iept-experiments@ivt.ntnu.no	OK SMS
	Gjennomgang av Swirl-rigg	OK SMS
	Gjennomgang av komponenter i rigg	OK SMS
	Gjennomgang av kritiske komponenter	OK SMS
	Driftsprosedyre	OK SMS
	Nødstopprosedyre	OK SMS
	Nærmeste brann/førstehjelpsststsajon	OK SMS
	Kunne forklare og svare på spørsmål om oppsettet	OK SMS

Jeg erklærer herved at jeg har gjennomgått og forstått HMS-regelverket, har fått hensiktsmessig opplæring for å kjøre dette eksperimentet og er klar over mitt personlige ansvar ved å arbeide i EPT laboratorier.

Operatør

Dato 30.04.2013

Signert Sigrid Marie Skoadje

VEDLEGG G: SKJEMA FOR SIKKER JOBB ANALYSE

SJA tittel:		
Dato:		Sted:
Kryss av for utfylt sjekkliste:		

Deltakere:		
SJA-ansvarlig:		

Arbeidsbeskrivelse: (Hva og hvordan?)
Risiko forbundet med arbeidet:
Beskyttelse/sikring: (tiltaksplan, se neste side)
Konklusjon/kommentar:

Anbefaling/godkjenning:	**Dato/Signatur:**	**Anbefaling/godkjenning:**	**Dato/Signatur:**
SJA-ansvarlig:		HMS koordinator	
Ansvarlig for utføring:		Annen (stilling):	

HMS aspekt	Ja	Nei	NA	Kommentar / tiltak	Ansv.
Dokumentasjon, erfaring, kompetanse					
Kjent arbeidsoperasjon?					
Kjennskap til erfaringer/uønskede hendelser fra tilsvarende operasjoner?					
Nødvendig personell?					
Kommunikasjon og koordinering					
Mulig konflikt med andre operasjoner?					
Håndtering av en evnt. hendelse (alarm, evakuering)?					
Behov for ekstra vakt?					
Arbeidsstedet					
Uvante arbeidsstillinger?					
Arbeid i tanker, kummer el.lignende?					
Arbeid i grøfter eller sjakter?					
Rent og ryddig?					
Verneutstyr ut over det personlige?					
Vær, vind, sikt, belysning, ventilasjon?					
Bruk av stillaser/lift/seler/stropper?					
Arbeid i høyden?					
Ioniserende stråling?					
Rømningsveier OK?					
Kjemiske farer					
Bruk av helseskadelige/giftige/etsende kjemikalier?					
Bruk av brannfarlige eller eksplosjonsfarlige kjemikalier?					
Er broken risikovurdert?					
Biologisk materiale?					
Støv/asbest/isolasjonsmateriale?					
Mekaniske farer					
Stabilitet/styrke/spenning?					
Klem/kutt/slag?					
Støy/trykk/temperatur?					
Behandling av avfall?					
Behov for spesialverktøy?					
Elektriske farer					
Strøm/spenning/over 1000V?					
Støt/krypstrøm?					
Tap av strømtilførsel?					
Området					
Behov for befaring?					
Merking/skilting/avsperring?					
Miljømessige konsekvenser?					
Sentrale fysiske sikkerhetssystemer					
Arbeid på sikkerhetssystemer?					
Frakobling av sikkerhetssystemer?					
Annet					

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FORSØK PÅGÅR /EXPERIMENT IN PROGRESS

Dette kortet SKAL henges opp før forsøk kan starte!

This card MUST be posted on the unit before the experiment startup!

Apparatur (Unit) Swirl-Rigg	**Dato Godkjent** (Date Approved)
Faglig Ansvarlig (Scientific Responsible) Torbjørn Nielsen	**Telefon mobil/privat** (Phone no. mobile/private) +4791897572
Apparaturansvarlig (Unit Responsible) Sigrid Skodje(student) Bård Brandåstrø (ansatt)	**Telefon mobil/privat** (Phone no. mobile/private) +4795155929 +4791897257
Godkjente operatører (Approved Operators) Sigrid Marie Skodje	
Prosjekt (Project) Swirl-rigg	**Prosjektleder (Project leader)** Torbjørn Nielsen
Forsøkstid / Experimental time (start - stop) April 13- Juni 13	
Kort beskrivelse av forsøket og relaterte farer (Short description of the experiment and related hazards) Drift av swirlrigg med ulike volumstrømmer og trykk Farer: støy, sprut, rørbrudd.	

NTNU
Institutt for energi og prosessteknikk

Dato 6/5 - 2013

Signert

SINTEF Energi
Avdeling energiprosesser

Dato

Signert

NTNU SINTEF

APPARATURKORT / UNITCARD

Dette kortet SKAL henges godt synlig på apparaturen!
This card MUST be posted on a visible place on the unit!

Apparatur (Unit) Swirl-Rigg	**Dato Godkjent** (Date Approved)
Faglig Ansvarlig (Scientific Responsible) Torbjørn Nielsen	**Telefon mobil/privat** (Phone no. mobile/private) +4791897572
Apparaturansvarlig (Unit Responsible) Sigrid Skodje(student) Bård Brandåstrø (ansatt)	**Telefon mobil/privat** (Phone no. mobile/private) +4795155929 +4791897257
Sikkerhetsrisikoer (Safety hazards) Støy, sprut, rørbrudd.	
Sikkerhetsregler (Safety rules)	
Nødstopp prosedyre (Emergency shutdown) Pumpa til rigg stoppes ved å trykke på nødstoppsbryter enten på østveggen ved peltonturbin eller inne i kontrollbua.	

Her finner du (Here you will find):

Prosedyrer (Procedures)	I perm ved rigg
Bruksanvisning (Users manual)	I perm ved rigg

Nærmeste (Nearest)

Brannslukningsapparat (fire extinguisher)	Ved inngangen til lunsjrommet
Førstehjelpsskap (first aid cabinet)	1.etasje ved utgang mot øst

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Dato 6/5 -2013

Signert [signature]

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Dato

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