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Development of a Francis Turbine Test Rig at Kathmandu University

Utvikling av en Francisturbin testrigg ved
Kathmandu University

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Mechanical Engineering
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MASTER THESIS

for
student Andreas Kjerschow
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Development of a Francis Turbine Test Rig at Kathmandu University
Utvikling av en Francisturbin testrigg ved Kathmandu University

Background

The Turbine Testing Laboratory at Kathmandu University was commissioned in 2011, and will be useful for future developments and improvements of hydraulic machinery necessary for the Nepali market and throughout the Himalaya region.

The laboratory is built up around a main pipe system, with the two main booster pumps located in the basement. Various running configurations are possible by utilizing different pipe loops, enabling both open and closed loop conditions. Kathmandu University are aiming to install test rigs equipped with high-precision measuring instruments in accordance with the IEC 60193 standard, enabling performance guarantee tests of Francis- and pump-turbines.

Recently, Kathmandu University received a grant from the Norwegian Government for a large research program named "Energize Nepal" where one activity is aiming to build a state of the art Francis turbine test rig. NTNU will support the development of this test rig by giving technical support from the Waterpower Laboratory.

The Francis turbine test rig is being used for research and development tests, along with model acceptance tests. The tests comprise determination of performances, such as efficiency, discharge, head and power. The operating behaviors are investigated, such as cavitation behavior and operation at runaway. The dynamic phenomena such as pressure fluctuations, torques and forces will also be investigated.

Objectives

Design the data logging system for the efficiency measurement of Francis turbines in the Turbine Testing Laboratory at Kathmandu University.

The following tasks are to be considered:

1. Literature study
    a. Get familiar with model testing of Francis turbines
2. Software knowledge
    a. LabVIEW
3. Waterpower laboratory at NTNU
    a. Get familiar with the LabVIEW program which is utilized for the Francis turbine
    b. Get familiar with the calibration of the instruments used in the test rig.
4. Turbine Testing Laboratory, Kathmandu University
    a. Get familiar with the existing system in the Turbine Testing Laboratory.
    b. Design a detail logging system for efficiency measurements based on LabVIEW-programs at the Waterpower Laboratory, NTNU.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☒ Work to be done in the Waterpower laboratory
☐ Field work

Department for Energy and Process Engineering, *February 10th, 2017.*

Ole G. Dahlhaug

Ole Gunnar Dahlhaug
Academic Supervisor

Co-Supervisors:

- Biraj Singh Thapa
- Bjørn Winther Solemslie

Preface

I heard about the Waterpower Laboratory and the interesting projects in cooperation with Kathmandu University through a friend at NTNU. For that, I am very grateful, due to the unique environment I have experienced here the final year as a master student – both socially and academically. The opportunity of being able to walk into the office of the professors, Ph.D candidates and other staff to get help whenever I needed has this project much more interesting and made it feel like we all were a team.

I am also very thankful for the stay at Kathmandu University, where the staff was very helpful and welcoming. It was very interesting to see how things were working in Nepal and to meet so many nice and positive people. I would like to thank Ravi Koirala, Biraj Singh Thapa and Atmaram Kayastha for the hospitality and the cooperation on the Energize Nepal project.

For the opportunity to be a part of all this and to work with a thesis towards Kathmandu University, I would especially like to thank my supervisor Ole Gunnar Dahlhaug. I also would like to thank Carl Bergan, Einar Agnalt, and Bjørn Winther Solemslie for all the help with programming in LabVIEW and for answering all my questions.

Andreas Kjerschow

Andreas Kjerschow

Trondheim, August 8, 2017

Abstract

Even though Nepal is situated between two of the fastest growing economies in the world, India and China, they still lag behind. With the worldwide change towards renewable energy, growing power demand and the vast hydropower potential in Nepal, the country possess an opportunity that can help the them thrive forward. That is why Kathmandu University developed the Turbine Testing Laboratory with support from Norwegian University of Science and Technology and Norad, among others. The laboratory is up and running, but still lack a lot of equipment to follow the *IEC 60193* [1] standard.

The first objective of this thesis was to analyze the laboratories at NTNU and KU, in addition to examine the procedures of model testing on Francis turbines in accordance to *IEC 60193* [1]. Considerable time has especially been used to understand the sensor and acquisition system at NTNU to further recommend a similar set-up for the laboratory at KU.

The main objective of the thesis was to make a full scale logging program in LabVIEW for the Francis test rig at KU. To carry out this task, the program used at NTNU was tested and analyzed first. Since staff and students at KU may reprogram the logging program in the future, much effort has been made to make the program easy to understand, yet have advanced functions. A user manual has been made for the new logging program and programming procedures are described thoroughly in the report.

Sammendrag

Selv om Nepal ligger mellom to av de raskest voksende økonomiene i verden, India og Kina, ligger de fortsatt et stykke bak. Med den verdensomspennende endringen mot fornybar energi, større etterspørsel av kraft og det store vannkraftpotensialet i Nepal, har landet en mulighet som kan hjelpe dem fremover. Dette er grunnen til at Kathmandu Universitetet bygget Turbine Testing Laboratory med støtte fra Norges teknisk-naturvitenskapelige universitet og Norad. Laboratoriet er oppe og går, men mangler fortsatt mye utstyr for å følge standarden *IEC 60193* [1].

Det første målet med denne oppgaven var å analysere laboratoriene ved NTNU og KU, i tillegg til å undersøke prosedyrene for modelltesting på Francis turbiner i samsvar med *IEC 60193* [1]. Mye tid har særlig vært brukt til å forstå sensor- og databehandlingssytmene ved NTNU, for videre å anbefale et lignende oppsett for laboratoriet på KU.

Hovedformålet med oppgaven var å lage et fullskala loggeprogram i LabVIEW for Francis testriggen på KU. For å utføre denne oppgaven, ble programmet som blir brukt på NTNU testet og analysert først. Siden ansatte og studenter ved KU skal kunne omprogrammere loggprogrammet ved en senere anledninger, har det blitt gjort mye arbeid for at programmet skal være lett å forstå, men allikevel ha avanserte funksjoner. En brukermanual er laget for det nye loggeprogrammet, og programmeringsteknikkene beskrives grundig i rapporten.

Contents

Nomenclature

Abbreviations

DAQ	Data Acquisition
DC	Direct Current
IEC	International Electrotechnical Commission
I/O	Input/Output
KU	Kathmandu University
masl	Meters above sea level
mwc	Meters water column
NI	National Instruments
Norad	Norwegian Agency for Development Cooperation
NPSH	Net Positive Suction Head
NTNU	Norwegian University of Science and Technology
PLC	Programmable Logic Controller
rpm	Revolutions per minute
rps	Revolutions per second
RSS	Root Sum Square
RTD	Resistance Temperature Detector
TTL	Turbine Testing Laboratory
VI	Virtual Instrument

Symbols

A_1	Inlet area - at pressure measurement	m^2
A_2	Outlet area - at pressure measurement	m^2
D	Diameter of runner	m
E	Specific hydraulic energy	J/kg
$(e_Y)_r$	Random uncertainty for quantity Y	Unit as Y
$(e_Y)_s$	Systematic uncertainty for quantity Y	Unit of Y
$(e_Y)_t$	Total uncertainty for quantity Y	Unit of Y
$(f_Y)_r$	Random uncertainty for quantity Y	-
$(f_\mathrm{Y})_s$	Systematic uncertainty for quantity Y	-
$(f_\mathrm{Y})_t$	Total uncertainty for quantity Y	-
g	Acceleration of gravity	m/s^2
H_e	Effective head	m
n	Rotational speed	rpm
n'	Rotational speed – used for n_{ED}	rps
n_{ED}	Speed factor	-
p	Pressure	Pa

P	Shaft power at generator	W
P_h	Hydraulic power	W
$P_{L,m}$	Mechanical power loss	W
P_m	Mechanical power at runner	W
Q	Volumetric flow	m^3/s
Q_{ED}	Discharge factor	-
S_Y	Sample or estimated standard deviation for quantity Y	Unit of Y
T	Main shaft torque at generator	Nm
$T_{L,m}$	Bearing friction torque loss	Nm
T_m	Main shaft torque at runner	Nm
v_1	Inlet velocity - at pressure measurement	m/s
v_2	Outlet velocity - at pressure measurement	m/s
α	Guide vane angle	degrees
Δp	Differential pressure	Pa
Δz_M	Height difference between sensors	m
η_h	Hydraulic efficiency	-
ρ_w	Density of water	kg/m^3
σ	Thoma number	-
ω	Angular velocity	rad/s

Specific symbols used for uncertainty analysis

$(f_{\mathrm{E}})_s$	Systematic uncertainty in specific hydraulic energy	-
$(f_{\mathrm{T_m}})_s$	Systematic uncertainty in runner torque	-
$(f_{\mathrm{Q}})_s$	Systematic uncertainty in flow	-
$(f_{\mathrm{\eta_h}})_r$	Random uncertainty in hydraulic efficiency	-
$(f_{\mathrm{\eta_h}})_s$	Systematic uncertainty in hydraulic efficiency	-
$(f_{\eta_h})_t$	Total uncertainty in hydraulic efficiency	-
$(f_{\omega})_s$	Systematic uncertainty in rotational speed	-
$(f_{\rho_w})_s$	Systematic uncertainty in water density	-

1 Introduction

At the Norwegian University of Science and Technology, the Waterpower Laboratory is one of the oldest buildings at the campus. It was ready to use in 1917 and was built to improve the knowledge about hydropower and to increase the efficiency on the turbines built in Norway [2]. In Nepal, hydropower has been utilized since 1911, but most of the knowledge and procedures of building are coming from foreign countries [3]. That way, a large scope of job and revenue opportunities disappear from Nepal. In addition, the imported turbines are often designed for countries with clean rivers and therefore the power companies in Nepal lose a lot of revenue due to the huge problem of sand erosion in the Himalayan region. This is why Kathmandu University (KU) established a research department and built the Turbine Testing Laboratory (TTL). The laboratory is already in use for research, but still lack a lot of crucial equipment to perform certified model tests.

The writer and his fellow student Morten Grefstad visited Nepal and TTL in April and May 2017. During the trip, vast problems of sand erosion throughout the country and lack of equipment in the laboratory was observed. The trip gave an even bigger inspiration for delivering a good thesis that could be used for future students and employees at the TTL, KU.

One of the tasks in this thesis is to learn how model tests for Francis turbines are done in compliance with the standard *IEC 60193* [1] at the Waterpower Laboratory, NTNU. To achieve this, literature studies, calibrations and efficiency tests has be carried out. Another task is to get familiar with existing system at the laboratory, both at NTNU and KU. The theory regarding these tasks are presented in chapter 2 and 3.

The last task in this thesis is to learn the Nation Instruments program called LabVIEW and use it to produce a full scale logging system for the future IEC certified test rig at KU. The program used at NTNU has been studied and some parts of it has been used as an inspiration for the design of the program for TTL.

2 Background

Chapter 2.1-2.3 is partly based on the equivalent chapters in the project thesis of Inger Johanne Rasmussen [3].

2.1 Previous work

The Turbine Testing Laboratory (TTL) at Kathmandu University (KU) has the purpose of testing the performance of model turbines, as well as gaining knowledge on how to handle the problem of sand erosion in turbines. Norwegian Agency for Development Cooperation (Norad) and the Waterpower Laboratory at the Norwegian University of Science and Technology (NTNU) has been important players in realizing TTL. The cooperation between KU and NTNU have been strong, resulting in a design of TTL, which is mostly inspired by the Waterpower Laboratory at NTNU. Several research projects have been executed, at both KU and NTNU, with the target of reaching the standards of *IEC 60193* [1].

The students that so far have been working towards the design of the Francis turbine test rig in TTL at KU:

- Jonas Bergmann-Paulsen, 2012: In his project and master thesis, he designed and performed FSI-analysis on a new full scale Francis turbine for it to withstand sand erosion. This was done with regard to the Jhimruk Power Plant in Nepal and was a cooperation between NTNU and KU [4].
- Bidhan R. Halwai, 2012: Designed a downscaled Francis turbine test rig from the 3D drawing of Mr. Bergmann-Paulsen, including proposal for positions of the turbine, piping and measurement instruments in his project thesis [5].
- Johanne Seierstad, 2013: Made a proposal for the flow calibration system and flow meter in her master thesis [6].
- Inger Johanne Rasmussen, 2014: Made a proposal for the pressure tank, draft tube tank, guide vane control system, main shaft, bearing block, instrumentation and power electrical system in her master thesis [7].
- Magomed Selmurzaev, 2016: Designed the measurement setup for friction torque and axial load in his master thesis [8].

- Morten Grefstad, 2017: Made a new design for friction torque and axial load in his master thesis [9].

2.2 The Waterpower Laboratory at NTNU

Since most of the design of TTL at KU will be based on the Francis turbine test rig at NTNU, it is important to understand how the test rig is built, operated and monitored at NTNU. The way the test rig is built satisfies the standards in *IEC 60193* [1].

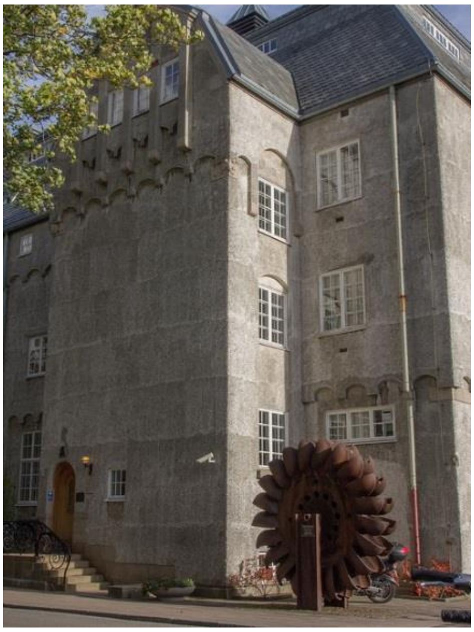


Figure 2.1: Outside the Waterpower Laboratory at NTNU. Photo: NTNU.

The test rig is getting its water from a large reservoir placed in the basement of the building and the water is provided to the pipe system by two large pumps of 330 kW. These can be operated in series or parallel, providing respectively maximum 100 meter water column (mwc) at 0.5 m^3/s and 1 m^3/s at 20 mwc [10].

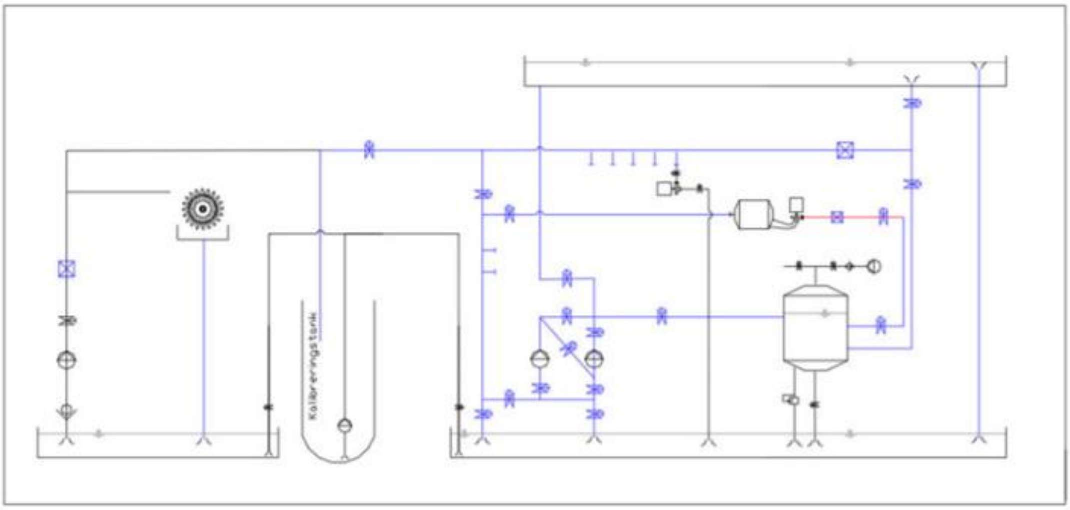


Figure 2.2: The main pipe system at the Waterpower Laboratory at NTNU.

The Francis test rig can be operated in two different modes, open loop or closed loop. In open loop, the water is pumped to an upper reservoir with free water surface, meaning that this will be the pressure line for the turbine. The upper reservoir is big and have overflow channels so that minor variations in pump speed and turbine/generator speed does not influence the hydraulic head. From here, the water flows through the high-pressure tank and into the turbine. On top of the turbine rig there is a 352 kW DC generator that convert the torque provided from the turbine to electrical energy. After extracting the energy in this mode, the water runs down in the lower reservoir.

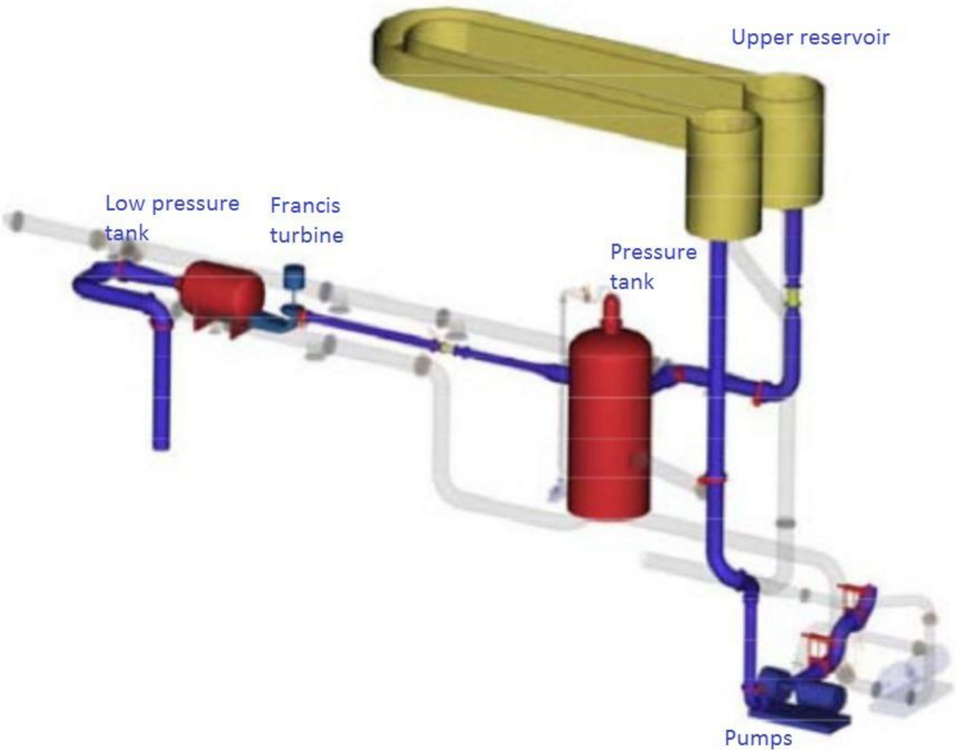


Figure 2.3: The Francis test rig at NTNU in open loop mode.

In closed loop, the lower and the upper reservoirs are skipped and the pipes are completely flooded. The only places where air bubbles aggregate is in the top of the high-pressure tank and the draft tube tank. By pumping the air in or out from the top of the draft tube tank, it is possible to change the submergence of the turbine [11].

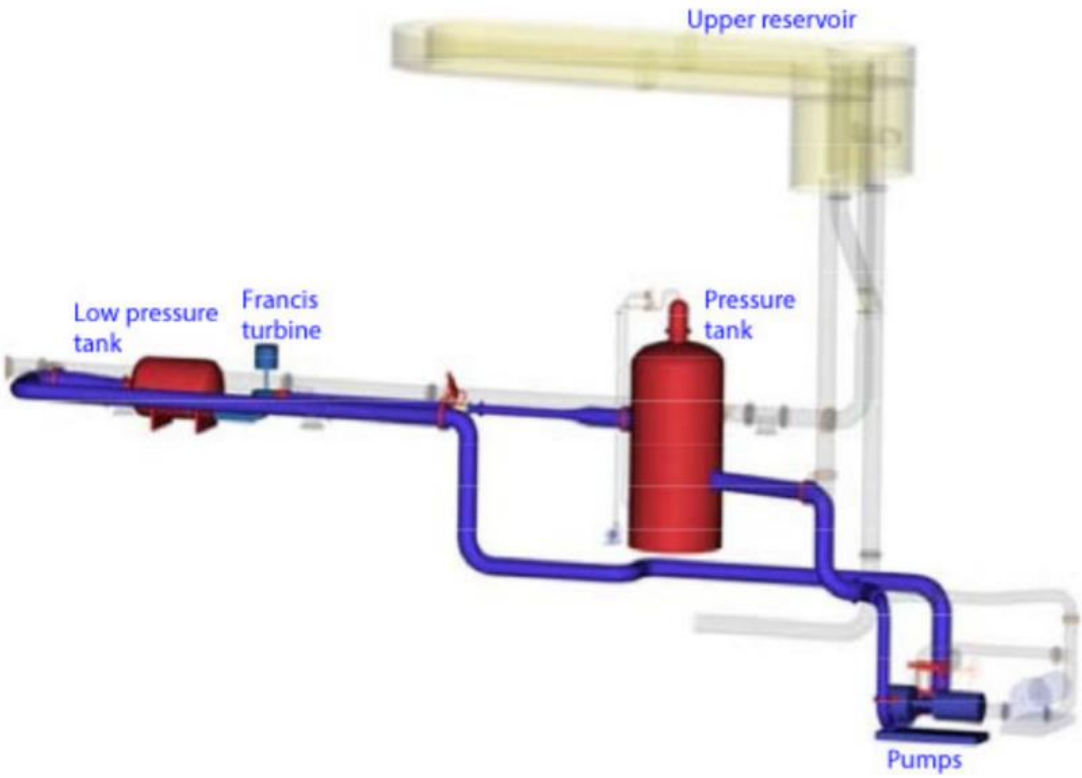


Figure 2.4: The Francis test rig at NTNU in closed loop mode.

The performance of the turbine is mainly measured by analog transducers, apart from the rotational speed measurement. On this measurement; both an analog and a digital sensor is installed, but the digital is most often used. The monitoring/logging system and sensors are described further in chapter 3.

2.3 The Turbine Testing Laboratory at KU

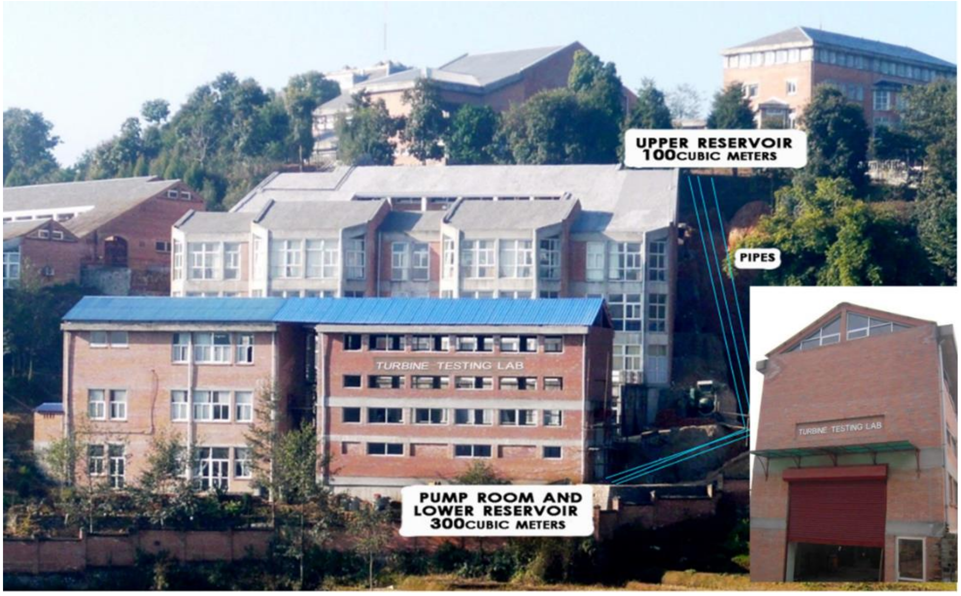


Figure 2.5: The outside of the Turbine Testing Laboratory (TTL) at Kathmandu University (KU) [31].

Nepal is a country with a potential of huge hydropower resources, both regard to heavy precipitation and large altitude differences. This potential was barely utilized until the Hydropower Development Policy was formulated in 1992. It was made to encourage national and international private sector to invest in hydropower development in Nepal. Nationally, there was a lack of knowledge on hydropower and a need for local research arose.

The process of designing the Turbine Testing Laboratory at Dhulikel campus of Kathmandu University – School of engineering, started in 2000. The construction phase was finally finished in 2011 and Nepal's first hydropower laboratory could open.

The building is situated in a hillside which made it possible to make an upper reservoir mounted outside with a capacity of 100 m^3. This provides the turbine with 30 m static head. The lower reservoir is the main reservoir and is in the basement of the building. Since it is the main reservoir, it has an capacity of 300 m^3.

Two centrifugal pumps of 250 kW are installed in the basement of the building to carry the water from the lower to upper reservoir. The pumps can be operated in series or parallel, producing a maximum head of 150 m or a maximum flow of 0.5 m^3/s. This is contradictory compared to the specifications of the laboratory at NTNU, but is due to the limitations in the pipe system and not only due to the effect the pumps can deliver [11]. These limitations and the limitations of the generator makes it possible to make tests on turbines up to 300 kW [12].

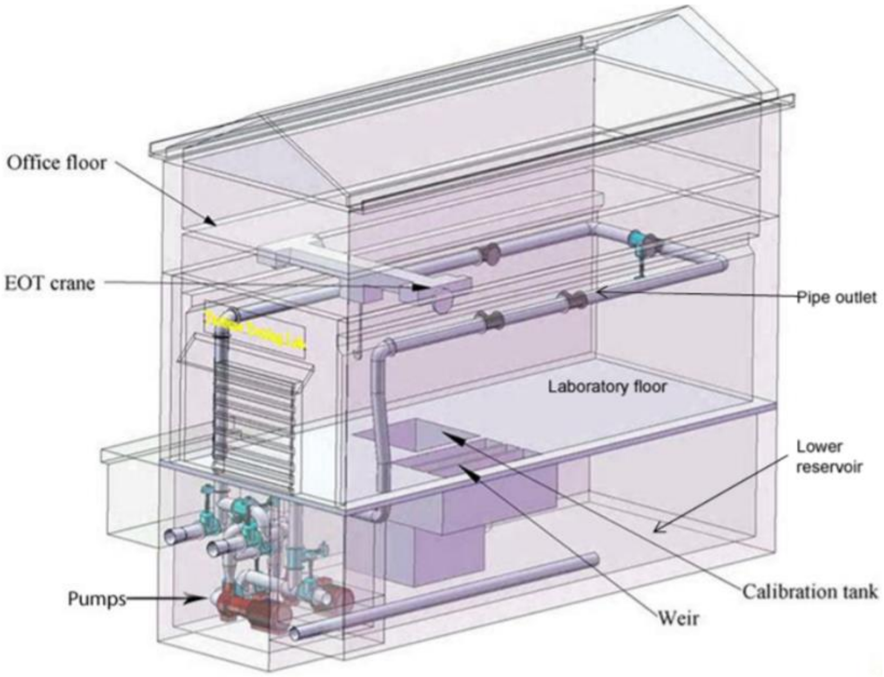


Figure 2.6: Inside the Turbine Testing Laboratory (TTL) at Kathmandu University (KU) [34] .

The Francis test rig that now is installed in the laboratory is a simplified version designed by the staff and the students at KU. The test rig lack a lot of essential components and sensors and is not certified by any means. The plan for the upcoming years is to build a new Francis test rig with generator, sensors and monitoring equipment in accordance with the *IEC 60193* [1]. Staff and students from both KU and NTNU are cooperating and have already started on making the new design.

Figure 2.7: The simplified Francis turbine test rig at TTL. The rig was dismantled for maintenance when the writer visited KU in 20017. Photo: Biraj Sing Thapa.

The purpose of the lab is to build competence and knowledge for the hydropower sector in Nepal. It is going to be a teaching facility for students, industrial companies and their staff. Due to this, it will work as a meeting place for the industry and the university. The main research sectors will according to TTL be “development of efficient turbines able to withstand sand erosion, development of turbine and pump technology and maintenance of turbines” [12].

2.4 Other laboratories

Even though the hydropower technology is based on old inventions, there is still a lot of uncharted areas. As the world is leaning more and more towards renewable energy, it will be more important to optimize the hydro power potential and look for new ways to utilize the technology. That is why there is a lot of laboratories with test rigs around the world. The various turbine manufacturers usually have their own test rig, which are mainly used for industrial purposes.

Some test rigs are owned by universities or organizations were the main purpose is research and educational use. As both NTNU and KU share this ideology, other test rigs for research and educational use around the world is mentioned here:

Turboinštitut is situated in Ljubilana, Slovenia and deliver model test in compliance with *IEC 60193* [1]. They also optimize geometry in processes of refurbishing old turbines [13].

Laboratory for Hydraulic Machines, LMH, is situated at University of Lausanne, in Switzerland. Their main expertise on hydraulic machinery concerns model testing and field testing of turbines. They have 3 different test rigs which can be adjusted to fit most types of hydraulic turbines, storage pumps and pump-turbines. The laboratory is built in compliance with *IEC 60193* [14].

Mhylab is a mini-hydraulics laboratory for small hydro power turbines, situated in Switzerland. Among other things, they provide efficiency and power curves for different types of turbines [15].

Institute of Hydraulic Fluid Machines, HFM, at Graz University of Technology, Austria also has a laboratory. This laboratory is certified by various IEC and ISO standards, including

IEC 60193. Their main activities is plant, operating and life-cycle tests, model acceptance tests, duration tests and comparing experimental data to simulated data [16].

Laboratory for Hydraulic Engineering is found at University of Stuttgart, Germany. Their field of activity is researching development and operational behavior for hydraulic machinery [17].

Hydraulic Machines Laboratory is a part of Laval University in Québec, Canada. Their goal is to provide model tests, cavitation tests, R&D studies and train highly qualified people for the hydro industry. The test rig is in compliance with ICE 60193 [18].

Alternate Hydro Energy Centre, AHEC, is built at Indian Institute of Technology (IIT) in Roorkee. The laboratory is meeting *IEC 60193* and IEC 17025 requirements [19].

Central Water and Power Research Station (CWPRS) has a laboratory for hydraulic performance and overload tests on submersible pumps. This laboratory is situated in Pune, India [20].

Älvkarlebylaboratoriet is located in Sweden and is owned by the state-owned company Vattenfall Utvekling AB. They perform efficiency tests and cavitation tests in compliance with *IEC 60193* [21].

2.5 The Francis turbine

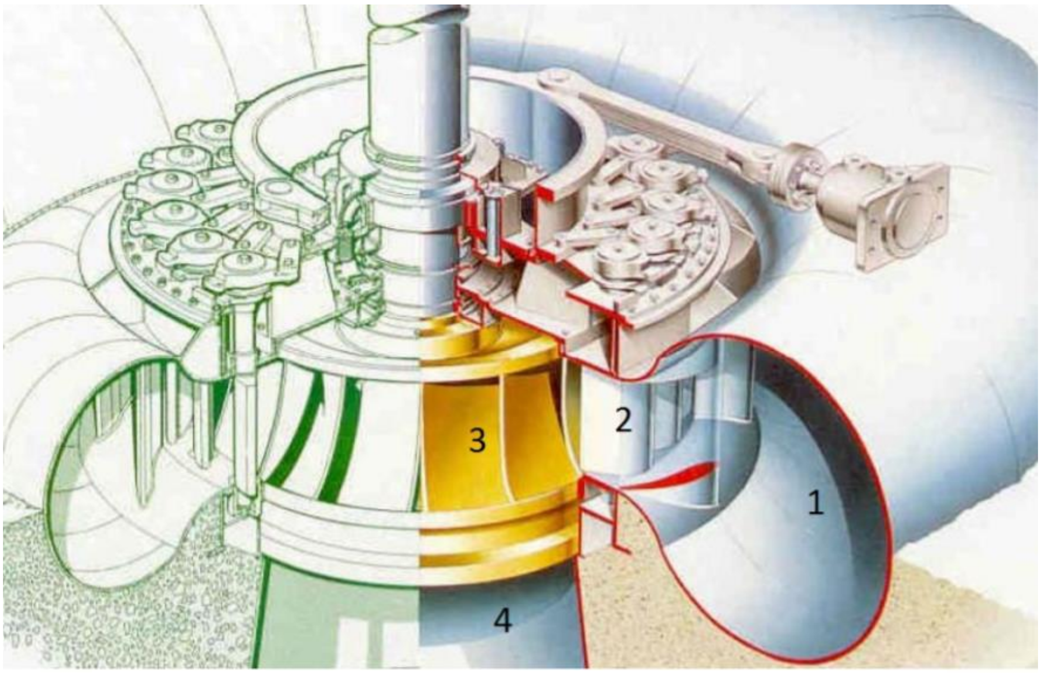


Figure 2.8: Cut out view of a Francis Turbine [27]

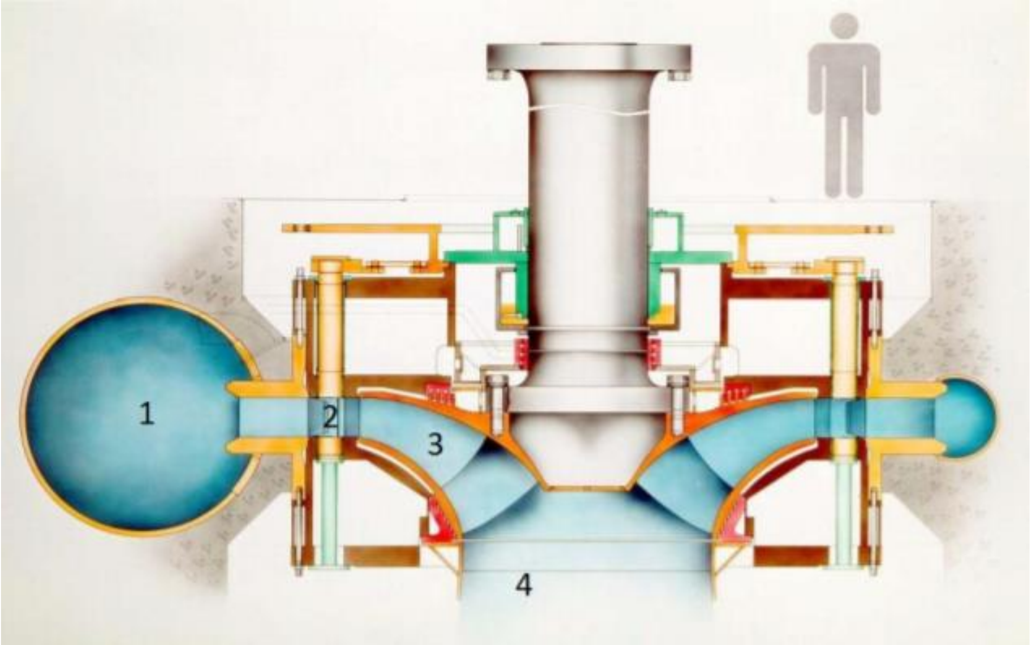


Figure 2.9: Sectional view of a Francis turbine [27]

The Francis Turbine is a reaction turbine, which means that the turbine and the pipes and tunnels both upstream and downstream is fully submerged in water. The definition also say that around half of the energy at the inlet of the turbine is due to the pressure difference between the inlet and the outlet of the turbine [7]. The Francis turbine is having the best efficiency on the market, but does not have the advantage of the flatter efficiency curve as the

Pelton turbines have. The Francis turbines can be produced for a large variation of heads and flows, but have a practical limit for conventional turbines of 750m head [22]. The turbine mainly consists of the following parts and the numbers correspond to Figure 2.8 and Figure 2.9:

1. **The spiral casing** distributes the water through the stay vanes in the spiral casing and lead the water to the guide vanes. This way the flow conditions are made as smooth as possible [23].
2. **The guide vanes** regulate the flow through the turbine and rotate the water from the spiral casing onto the runner blades with the right flow angle. The guide vanes are moved synchronously in the right position by a motor [23].
3. **The runner** is converting the energy in the water to mechanical energy. It is mounted on a shaft that is connected to a generator [23].
4. **The draft tube** is shaped like a cone to reduce the flow velocity towards the outlet and by this, increase the total pressure over the turbine. This gives the turbine a higher efficiency [23].

3 Model tests on Francis turbines

3.1 Model testing

Since most hydro power stations are very big, it is neither practical nor economical beneficial to perform field tests on such turbines. The most common procedure is to use models instead, which often are cheaper and provides a smaller uncertainty [24]. To correlate a model to a prototype, it needs to be geometrically and hydraulically similar. Geometrical similarity means that the wetted areas of the model has the exact same shape as the prototype, except that the dimensions are smaller.

Hydraulic similarity means that there are identical ratios of various forces acting between the fluid and the components of the turbine rig. These ratios are defined through the dimensionless terms presented in *IEC 60193* [1]: Reynolds number ($\mathrm{Re} = \frac{\mathrm{inertia}}{\mathrm{viscosity}}$), Euler number ($\mathrm{Eu} = \frac{\mathrm{pressure}}{\mathrm{inertia}}$), Froude number ($\mathrm{Fr} = \frac{\mathrm{inertia}}{\mathrm{gravity}}$), Weber ($\mathrm{We} = \frac{\mathrm{inertia}}{\mathrm{surface\ tension}}$) and

Thoma number (or Thoma cavitation number) ($\sigma = \frac{\text{net positive suction specific energy}}{\text{specific hydraulic energy}}$).
In general, it is impossible to satisfy the different similitude numbers simultaneously. Therefore, the similitude number with the greatest impact on the result should be considered. Since it is difficult to achieve the exact same similitude number on the model, as on the prototype, minor corrections need to be done when the efficiency result are transformed to the prototype conditions [1]. For example, is the efficiency often higher on prototype turbines than what is achieved on the model, because of the difference in Reynolds number and relative roughness.

The above dimensionless terms, is the theoretical description of hydraulic similitude. It can also be shown by the basic terms above, that a model and prototype is operated at hydraulically similar conditions by checking the ratios of corresponding flow velocity components at any point in the different turbines. At corresponding operating points, the turbines thus will have the same discharge factor, speed factor and as mentioned above, Thoma number. These coefficients is calculated by the following equations:

$$(Q_{ED})_{model} = (Q_{ED})_{prototype} = \frac{Q}{D^2\sqrt{gH_e}} \tag{3.1}$$

$$(n_{ED})_{model} = (n_{ED})_{prototype} = \frac{n'D}{\sqrt{gH_e}} \tag{3.2}$$

$$\sigma_{model} = \sigma_{prototype} = \frac{NPSH}{H_e} \tag{3.3}$$

Q represents the flow, D is the runner/impeller diameter, H_e is the effective turbine head, n' is the rotational speed (mark: in this equation used with the unit rps – revolutions per second) and NPSH is the Net Positive Suction Head. NPSH and σ is related to the submergence of the turbine and the potential for cavitation. This is further described in *Pumper og turbiner* [22] and *Grunnkurs i hydrauliske strømningsmaskiner* [23].

3.2 Instrumentation

Instrumentation, according to *IEC 60193* [1], is divided into two different categories, namely primary methods and secondary methods. The primary methods performs measurements on fundamental quantities only; length, mass and time. The secondary instrumentation needs to be calibrated against a primary method to provide as accurate results as possible [1].

All the instrumentation used for the Francis rig at NTNU, except the rotational speed sensor, is analog. They measure a voltage level between 0-10 V. Multiplied with the linear calibration constants, they provide measurements with the desired unit. In this chapter, the sensor set-up at NTNU will be further explained.

The sensors can be connected to the computer in many different ways, either by premade and documented DAQs and modules, or by hand built hardware solutions. To hand build a solution for processing the sensors can be much cheaper, but can be very difficult and time consuming. It can also arise problems when connected to the computer software. Without a technician with advanced skills in electronics, this option is not recommendable. In most cases, premade DAQs and modules from various brands are used. NTNU uses DAQs and modules from National Instruments, as the company also make the software NTNU utilize for data logging. NIs devices are durable, stable and are easily connected and used towards computers with their software installed.

If you are having problems with your sensor or acquisition system, NI has lots of good manuals and tips for all kinds of scenarios at their webpage. It is recommended to use their database when setting up a test rig.

3.2.1 Pressure measurement

For calculating the effective head, the differential pressure is needed. This can either be measured with a single differential pressure transducer or having two gauge pressure transducers mounted at the same elevation. The only difference is that the gauge pressure transducers have two raw measurements and a minor calculation is needed for finding the differential pressure. If the gauge sensors are not installed at the same level, the height difference must be accounted for. Regardless of what you choose, plastic tubes are connected from the sensor to where the flow are as stable as possible; at the end of the inlet pipe and at the end of the draft tube pipe. In the expressions for head and efficiency, you need to find the correct density as well. This is calculated from iterative functions were the parameters are mean absolute pressure and temperature (see more on this in chapter 3.4). An atmospheric pressure transducer is therefore also needed. The difference in atmospheric pressure from the inlet to the outlet is, according to *IEC 60193* [1], negligible and thus the exact positioning of the sensor is not crucial.

The transducers installed at NTNU are differential pressure transducers. That means you only use one sensor to find the differential pressure. In some cases, the costumers of the model test will ask for which absolute inlet or absolute outlet pressure the test was performed at. Thus, the waterpower laboratory also has a sensor measuring gauge inlet pressure and a sensor measuring absolute atmospheric pressure. The inlet pressure transducer is connected to the same tubing as the inlet side of the differential pressure transducer. The transducers are manufactured by Fuji Electronics and are considered as secondary methods of measurement [3]. As a result, they must be calibrated frequently. A deadweight manometer carries out this task.

Figure 3.1: Deadweight manometer similar to the one at NTNU. Used for calibrating pressure transducers. Model: Fluke P3000 [36].

3.2.2 Flow measurement

At the Waterpower Laboratory, an electromagnetic flow meter is installed in the long, straight pipe between the pressure tank and spiral casing. This is done to obtain as stable measurements as possible. Exactly how long the pipes at both sides of the sensor should be, can usually be found in the product manual of the flow meter. Based on Faraday's Law of Electromagnetic Induction, a voltage will be generated when a conductive liquid is flowing through a magnetic field. The electromagnetic flow meter is making this magnetic field and electrodes on the inside of the pipe measure the magnitude of voltage [25].

This is a secondary method of measurement and needs to be calibrated frequently. This is done by using a weighing tank, a splitting screen and a counter. When calibration is initiated, the splitting screen lead the water in the pipe system into the weighing tank for time the counter has been set to. If the water density is known, you can calculate the flow from this and correlate it to the analog flow meter signals.

3.2.3 Rotational speed measurement

At the NTNU laboratory, the rotational speed measurement is done on the lower part of the shaft, above the turbine sealing. An apertured disc is mounted on the shaft and pass through an optical sensor. The digital sensor observe each passing and LabVIEW count the time between the signals. This is further used to calculate the rotational speed. Since time is a fundamental quantity, this is considered a primary method of measuring and does not need to be calibrated [26].

3.2.4 Torque measurement

Torque is measured two different places in the Francis rig at NTNU and must not be confused as the same. The generator torque is measured at the top of the shaft and the friction torque is measured at the bearing block. The torque is measured with load cells from HBM and is considered a secondary method. According to *IEC 60193* [1], they must thus be calibrated frequently.

3.2.5 Axial thrust measurement

The bearing block at in the Waterpower Laboratory at NTNU is a complex assembly of parts and lets the axial thrust be measured quite different from many other laboratories around the world. The bearing block has a closed chamber filled with oil and separated with axial thrust bearing. A differential pressure transducer is connected to each side of the axial thrust bearing. The transducer is measuring pressure difference in the oil and is used for calculating the axial thrust force [2].

This is a secondary method of measurement and must be calibrated frequently. As with the pressure sensors, this can be done with a deadweight manometer on the system at NTNU.

3.2.6 Guide vane angle

At NTNU, a new sensor mounted on top of one of the guide vane axles measures the guide vane angle. The sensor is digital, but converts the signal to analog. A full digital sensor has earlier been used, but is not recommended due to difficulties with programming and splitting the signal.

3.2.7 Temperature measurement and oxygen level

Temperature is used to determine the water density and is measured downstream the pressure tank in the Waterpower Laboratory. A RTD-sensor called PT100 is used where the resistance changes proportionally with temperature in the material. Depending on how many wires a RTD-sensor have the connection strategy changes. For 2- and 3-wire sensors, a Wheatstone bridge is often used, but for 4-wire systems, a constant current generator is used.

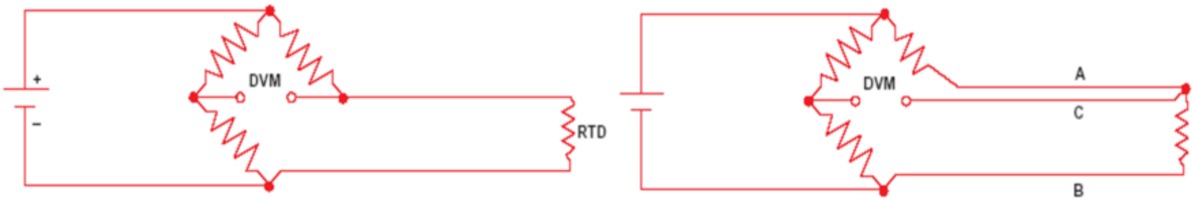


Figure 3.2: How to connect 2- and 3-wire RTDs with use of Wheatstone bridge. DVM is where the voltage is measured [37].

An even simpler method is to connect the PT100 sensor in a serial loop with a resistance and a voltage source. If the voltage over the resistance is measured, it will vary almost proportionally with the temperature in the sensor. This is not the most accurate way of doing it, but as a ± 0.5 °C variation in temperature corresponds to around $0.1 \frac{kg}{m3}$ in density, the connection type is more than accurate enough for its purpose. From basic electro, it is known that a current going through a resistance is generating heat. Thus, independent of how the sensor is connected, the current should be as small as possible to avoid heating the sensor.

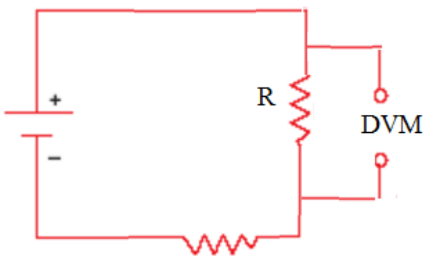


Figure 3.3: The easiest way to connect a RTD sensor. As done at NTNU.

The amount of dissolved oxygen in the water may at certain levels, change the performance of the runner. This is measured at the inlet pipe of the pump system in the basement of the Waterpower Laboratory. The sensor measuring this, is made by WTW. The method is based on diffusion of oxygen through a Poly Tetra Fluorine Ethylene membrane [3].

These sensors must be monitored in order to run model tests in compliance with *IEC 60193* [1]. External suppliers calibrate both sensors mentioned in this chapter.

3.3 Calibration

Before model tests, calibration of all instrumentation, not performing primary measurements, must be carried out. This is done to check for possible malfunctions to the sensors and acquisition system and work as a result validation for the model test. Depending on which type of tests you shall run, different instruments are calibrated. Some sensors are logged manually with pen and paper, but most are logged through data programs. Programs like this has been made at NTNU by using the software LabVIEW. It is made by National Instruments and is a graphical dataflow program that work with most measurement systems on the market. In this way, the program is very flexible and performs well as a data logger. If calibrations are done often, it is recommended to make an automated program for producing calibration reports. These reports should include measurement data, regression charts, calibration constants and random uncertainty for the calibration results. The last mentioned parameter will later be used to calculate the systematic uncertainty for the result data of the model test. To find out more about uncertainty, see chapter 3.5.

IEC 60193 [1] states that "recalibrations during tests may be necessary if serious problems with the standard measuring equipment occur". The same apply if any of the parties desire it to be recalibrated [1]. It is recommendable to always recalibrate the equipment even though it is not required from *IEC 60193* [1]. It is good to have a recalibration result to show if a lawsuit is done with regard to a model test.

To read more detailed procedures for calibrating the test rig at the Waterpower Laboratory, see Andrea Strannas project thesis [27].

3.4 Efficiency test

When hill and efficiency diagrams are made for turbines, it is the hydraulic efficiency explained in *IEC 60193* [1] that is used. That means that hydraulic and volumetric losses are included, but not the mechanical losses. In the standard just mentioned, hydraulic efficiency is defined as:

$$\eta_h = \frac{P_m}{P_h} = \frac{P + P_{L,m}}{\rho_w g Q H_e} \tag{3.4}$$

In this formula, P_h is the hydraulic power available for producing power, where Q is the volumetric discharge at the inlet of the turbine, g is the acceleration of gravity, ρ_w is the density of water and H_e is the effective head. P_m is mechanical power delivered from the runner to the connection of the shaft, P is mechanical power that the generator has available on top of the shaft, $P_{L,m}$ is the mechanical power losses in bearings [1]. Losses in shaft seals is, according to *IEC 60193* [1], included in $P_{L,m}$, but with the rig set-up in the Waterpower Laboratory, it is included in P instead. As these two are added together when calculating η_h, it doesn't make any difference on the final result.

As seen in the above equation, one need to find P, $P_{L,m}$, Q and H_e to find the hydraulic efficiency. P and $P_{L,m}$ are found by multiplying the corresponding torques with the angular velocity of the turbine:

$$P = T\omega \tag{3.5}$$

$$P = T_{L,m}\omega \tag{3.6}$$

The change of water density from the inlet to the outlet is according to *IEC 60193* [1], negligible when the head is less than 40 m. That does not mean it is possible to use an approximate value for water density. It must still be calculated from one of two empirical calculations where the absolute pressure and the water temperature is the parameters used. The two water density formulas for temperature ranging 0-20 ºC and 20-50 ºC can be found at page 169-171 in *IEC 60193* [1]. So, to validate the calculations for heads above 40 m as well, the mean absolute pressure is used instead. This is found by adding the absolute inlet pressure and the outlet pressure together and divide it on two.

$$p_{abs,1} = p_{M,1} + \rho_1 g(z_{M1} - z_1) + p_{amb} =^{*} p_{M,1} + p_{amb} \tag{3.7}$$

$$p_{abs,2} = p_{M,2} + \rho_2 g(z_{M2} - z_2) + p_{amb} =^{*} p_{M,2} + p_{amb} \tag{3.8}$$

$$p_{abs,mean} =^{*} \frac{p_{M,1} + p_{M,2}}{2} + p_{amb} \tag{3.9}$$

As the difference in atmospheric pressure is negligible compared to total pressure in system, the same value can be used at the inlet and outlet. Thus, the exact position of the atmospheric pressure sensor is not important. The simplifications marked with * can only be done if the two gauge sensors are mounted at the same level as, respectively, the center of the inlet and outlet pipes. To be specific, the center of the cross sections where the pressure taps are mounted. This is probably the best solution, as this will cancel out the second term in the formula for absolute pressure. That way, you skip the iterative process of having a density parameter in the formula when calculating density. If you nevertheless choose to have the sensors at a different position, you must choose a density in the calculation of the absolute

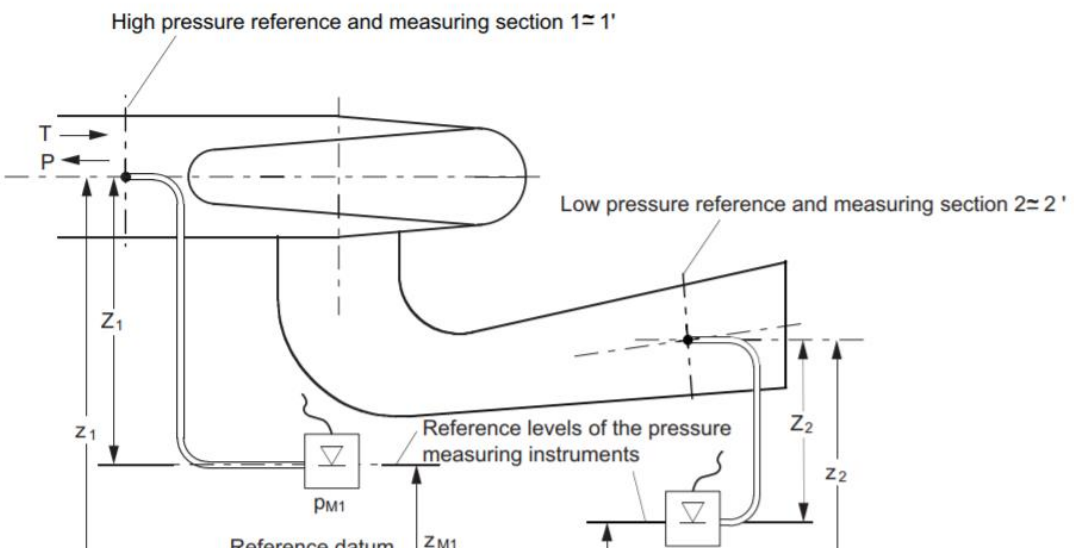


Figure 3.4: Drawing showing the different parameters when working with calculations on absolute pressure, density and head [3].

pressure that is assumed to be right and accept the minor uncertainty this calculation method provides. For the calculation of the density, the change in water temperature is also negligible and the temperature senor is often placed at the low-pressure side of the pipe system.

Q is found directly by using the flow meter. H_e is found by measuring the pressure difference over the runner and the velocity at the inlet and outlet of the runner:

$$H_e = \frac{\Delta p}{\rho_w g} + \frac{v_1^2 - v_2^2}{2g} = \frac{\Delta p}{\rho_w g} + \frac{Q^2\left(\frac{1}{A_1^2} - \frac{1}{A_2^2}\right)}{2g} =^{*} \frac{\Delta p}{\rho_w g} + \frac{Q^2\left(\frac{1}{A_1^2} - \frac{1}{A_2^2}\right)}{2g} + (z_{M,1} - z_{M,2}) \tag{3.10}$$

As shown at page 255-257 in *IEC 60193* [1], the level where the pressure sensors are installed, does not matter for calculating the differential pressure, as long as the two measurements are done at the same level. On the other hand, if you choose to use the already recommended method for calculating the density, the sensors cannot stay at the same level. That way, the elevation difference between the gauge sensors will be added to the head-formula shown in *IEC 60193* [1]. This is marked with * in the formula above. In the equation, Δp refers to the difference in gauge pressure and thus, the atmospheric pressure is not needed for this calculation directly. Further on, A_1 and A_2 is the inlet and the outlet area where the pressure taps are mounted. The term including Q is arrived by assuming that the flow at the inlet and the outlet is the same, and thus, the water leakage is negligible.

To produce a detailed hill diagram, the turbine is operated on constant head and the generator speed and the flow is changed. The various parameters are logged at the different operational points and the efficiency is plotted against the dimensionless parameters Q_{ED} and n_{ED}. The parameters can be processed in a spread sheet program such as Microsoft Excel, but the plotting is recommended to be done in MATLAB. Alternatively, the whole process may be executed in MATLAB. Codes for this can be found in appendix E.

3.5 Uncertainty analysis

Since model tests always have a certain degree of errors, it is important to tell something about the range within a measured quantity, were the true value can be expected to lie. Especially when hydro power plants are to be designed, the owners would like to have an uncertainty for the best efficiency point that they can compare with under the commissioning.

As in *IEC 60193* [1], the errors are divided in three groups in - spurious errors, random errors and systematic errors [1]:

1. **Spurious errors** are errors such as human errors or instrumentation failures. Measurements from these types of errors should be discarded.
2. **Random errors** are errors caused by various, small, independent influences which prevent the measurement system from delivering the same reading without changing the operational point. The uncertainty related to random errors can be reduced by increasing the number of measurements.
3. **Systematic errors** are errors having the same magnitude and sign under the same conditions of measurement. The uncertainty related to these errors will not be reduced by increasing the number of measurements. They are often a result of wrong calibrations or not precise enough calibrations.

As mentioned in chapter 3.3, an automated program for producing calibration reports with including calibration uncertainties should be made. The random and the systematic errors from the calibration of the instruments, corresponds to the systematic uncertainties in the model test. The random uncertainty in the model test is a result of the variation of data and the number of measurements done in each operational point.

For calculating the random uncertainty, the Student t-distribution is used. For data sets with many readings per operational points, the distribution will approach a Normal distribution. Even though it is more complex than the Normal distribution, it is also more precise for few readings. First, the sample standard deviation S_Y, or also called estimated standard deviation, is found where $\bar{Y}$ is the mean value of the distribution, n is the amount of measurements and Y_r is the value of each individual measurement:

$$S_Y = \left(\frac{\sum_{r=1}^{n} (Y_r - \bar{Y})^2}{n-1} \right)^{\frac{1}{2}} \tag{3.11}$$

Then, the random uncertainty for the distribution is a result of the t-coefficient, the estimated standard deviation and the amount of readings. The t-coefficient is found from a table or from empirical equations and is a function of confidence level and number of measurements. To stay in compliance with *IEC 60193* [1], a 95% confidence level is used. If more than approximately 1000 measurements are logged, the coefficient will be 1.96 – equal to a Normal distribution. For the following equations, the first has the same unit as the quantity measured and the second equation is a decimal or percentage if multiplied with 100.

$$(e_Y)_r = \pm \frac{(t \cdot S_Y)}{\sqrt{n}} \tag{3.12}$$

$$(f_Y)_r = \pm \frac{(e_Y)_r}{\bar{Y}} \tag{3.13}$$

To calculate the total uncertainty of a measured quantity from a model tests, the Root-sum-square (RSS) method is used. Here the RSS method is showed for an undefined quantity, with f_t representing the total uncertainty, f_s is the systematic uncertainty and f_r is the random uncertainty:

$$f_t = \pm\sqrt{f_s^2 + f_r^2} \tag{3.14}$$

The systematic and random terms in the equation above, may represent various associated parameters, depending on which quantity is being analyzed.

For example, is the total uncertainty for the hydraulic efficiency expressed like this:

$$\left(f_{\eta_h}\right)_t = \pm\sqrt{\left(f_{\eta_h}\right)_r^2 + \left(f_{\eta_h}\right)_s^2} \tag{3.15}$$

Here, the systematic term consist of the parameters showed below:

$$\left(f_{\eta_h}\right)_s = \sqrt{\left(f_Q\right)_s^2 + \left(f_E\right)_s^2 + \left(f_{T_m}\right)_s^2 + \left(f_\omega\right)_s^2 + \left(f_{\rho_w}\right)_s^2} \tag{3.16}$$

The writer of this thesis has carried out uncertainty analysis for the efficiency test done at NTNU prior to this master thesis. The calculations and the full symbol list for the uncertainty analysis can be examined in the writers' project thesis with same name as this thesis [28]. Further explanation on uncertainty analysis can be seen in *IEC 60193* [1] and *Compendium in instrumentation, calibration and uncertainty analysis* [26].

3.6 Programming in LabVIEW

As mentioned in chapter 3.3, LabVIEW is made by National Instruments and is used for making flexible and graphical monitoring systems, especially for laboratory tests. The dataflow programs made in LabVIEW are called Virtual Instruments (VIs.) A VI consist of two separate panels – a Front Panel and a Block Diagram. Compared to an old sensor monitor, the VI's Front Panel works as the display and the buttons, and the Block Diagram works as the monitor's brain. This way, it is possible to run numerous of different test set-ups, without changing the sensor connections. Instead, all sensors are connected to a computer

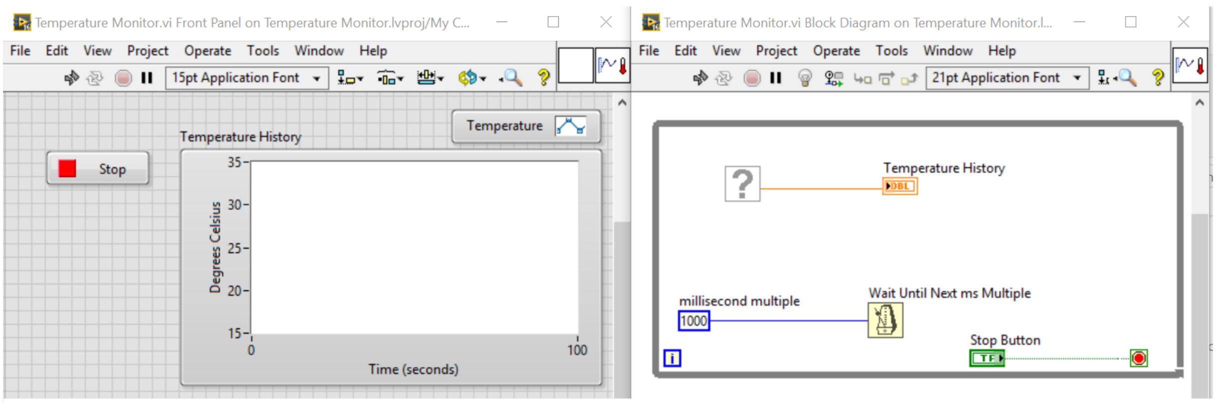


Figure 3.5: Example on a simple VI. Front panel on left side, block diagram on right side.

running VIs based on the need. The Block Diagram show how the signals from various sensors and buttons should be processed. A basic VI is presented in Figure 3.5:

When a logging system for efficiency measurements is programmed, there are mainly two different paths to choose from. Each of them can give the same result, but dependent on which features is needed in the program, one method can be easier to program than the other can. One option is to let the program run continuously and set how many seconds the operational points are logged. By doing this, it is easier to include functions for showing the operational parameters when the logging has stopped. A drawback with this path is that it sometimes have a small variation in the number of readings it generates over the logging time.

The other option is to set the number of readings the program should log. This way, you will have a constant number of readings, resulting in a data file that is easier to process retrospect to the testing. The drawback of this method is that it can be somewhat trickier to implement the functions giving operational parameters when the logging is finished.

To learn more about how to program in LabVIEW it is recommended to us NIs tutorials on their webpage. The writer of this thesis used the tutorial called Core 1 (v2015), but recently National Instruments uploaded lots of new tutorials, which can also be useful.

3.7 The logging program at NTNU

The program used for logging at the Waterpower Laboratory at NTNU is programmed after the State Machine-principle. The Block Diagram has a case structure with lots of different banners treating the scenarios that can occur after the program has started. Depending on which button you press, the code in the related banner is activated.

The program also has queue-system, added to handle situation of a full buffer while logging a test. This was added to the program to avoid data losses while doing tests on pressure pulsation cases. Pressure pulsation is a type transient test where the demand for sample rate is much higher than for steady state tests.

3.8 Precision of acquisition hardware and sensors

To acquire precise and trustworthy readings in LabVIEW, it is important to consider what needs you have for the test you will run, before buying the equipment. It can be tempting to go for the cheapest components, but it is not always the best solution if the test rig is meant to work in compliance with *IEC 60193* [1]. First, one must evaluate which kind of tests that will be executed. If a transient test is about to be set up, it is often more important with a high sample rate than in a steady state test. With a high sample rate, you can acquire more readings over a time period, which leads to a more detailed picture of what's really happening when you want to observe relatively quick changes in a process. It can be compared to a high velocity video camera.

Secondly, the precision of the reading depend on how many bit the DAQ and the modules can process. In general, it means how many digits behind comma you can rely on. A 12-bit module can divide the sensor span of each input into $2^{12} = 4096$ intervals. A 16-bit module, on the other hand, have $2^{16} = 65536$ intervals. That means you will achieve much more accurate readings from the sensor with more bits.

The third thing that is crucial when setting up an acquisition system is how the precision depend on the sensor span. As mentioned above, an amount of bits is equal to how many intervals you divide the sensor span in. This means that if the sensor span is very much bigger than what is needed for the tests, the precision will be lower than what is possible. For example, you expect 0-10 bar gauge pressure at a certain point in the one of the pipes in a test rig. You have a 12-bit module and a pressure sensor with a span of 500 bar. That means you potentially will have a $\frac{500}{4096} = 0.12207\ bar = 12207\ Pa$ deviation in your reading. Compared to a case with a 16-bit module and a sensor span of 20 bar, you will end up with a 30.5 Pa deviation instead. That is a very big difference, and the first option is not acceptable if your measurements are around 0-10 bar.

Forth, the number of connections used, sometimes affect the performance of a module. All modules not performing simultaneous readings have a maximum sample rate. For example the NI 9205 can maximum handle 250kS/s. If all 32 connections are used, this corresponds to 7812 samples per second per channel.

4 Results and discussion

4.1 Measurement and acquisition equipment at TTL, KU

For the test rig at Kathmandu University to follow the guidelines in *IEC 60193* [1], the equipment needed to be chosen with regard to both repeatability and uncertainty. In addition, since TTL does not have a technician with advanced skills within electronics at the time of writing, the measurement and acquisition system have to be easy to install, durable and open for future extensions with regard to more sensors.

Bård Aslak Brandåstrø, Bjørn Winther Solemslie and Ole Gunnar Dahlhaug have chosen some of the equipment, together with the researchers at TTL. Some of the equipment was already in the lab when the writer and his fellow student, Morten Grefstad visited TTL in April and May 2017, but this was mostly sensors that were used in other kinds of test set-ups or used with the simplified test rig. Some remaining measurement equipment has been chosen as a part of this master thesis, after various discussions and meetings with Ravi Koirala. Inputs from Ole Gunnar Dahlhaug and Bjørn Winther Solemslie have had strong influence in the choices made for the equipment.

A flow diagram has been made showing how the signals are going from the sensors, to different modules, to the DAQ device and into the computer. This can be seen in appendix A.

4.1.1 DAQ unit and modules

The option of making a handmade system is difficult and time consuming. Also, since TTL does not have an employee working entirely with electronics yet, the best alternative would be to go for commercial and well tested acquisition devices. National Instruments' DAQs and modules was the natural choice because they are durable, stable and because LabVIEW is made especially for these instruments. The Waterpower Laboratory at NTNU also have good experience with NIs equipment. The system planned for TTL is built around a NI cDAQ-9174 unit where four modules slots can be used depending on the need. As NI further explains their DAQ unit; "The chassis provides the plug-and-play simplicity of USB to sensor and electrical measurements. It also controls the timing, synchronization, and data transfer between C Series

I/O modules and an external host. You can use this chassis with a combination of C Series I/O modules to create a mix of analog I/O, digital I/O, and counter/timer measurements. The cDAQ-9174 also has four 32-bit general-purpose counters/timers [29].” The counter will be used together with the digital input channel when measuring rotational speed.

Furthermore, three modules will be inserted in the DAQ unit. All of this equipment was brought to TTL when the writer of this thesis visited KU. The most used module will be the NI 9205, accepting analog voltage signal. It has a 16-bit resolution and does not offer simultaneous readings from the different channels. Since the efficiency tests are done steady state, the need for total simultaneity is not needed. With a 250kS/s sample rate, the readings

Figure 4.1: The NI cDAQ-9174 without modules [28].

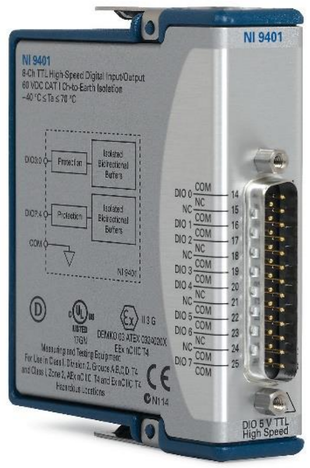


Figure 4.2: Example on a module. This is a digital I/O module, NI 9401, which will be used at TTL.

will be done almost at the same time anyway, and is more than sufficient. The module has 32 or 16 inputs, depending on how you connect the sensors. With a common reference connection, the module can handle 32 inputs and with separate reference connections for each sensor the module will handle 16. To avoid noise, it is recommended to use the option with 16 differential ports, as this connects the sensor to the module with two wires, instead of one. This way, it is easier to twist the signal and the reference wire together. That makes the noise inflict both wires simultaneously and the differential level will be zero. The downside of using a differential is the fluctuating voltage level, which in some cases can occur when using different references for the zero-voltage level. As long as one is aware of it, this can be avoided by grounding the equipment properly.

Current output is also an option for many sensors, and since some of the sensors already existing at TTL uses this option, a NI 9203 module was also needed. This also has a 16-bit resolution and does not handle simultaneous readings. This has a slightly lower sample rate, 200 kS/s but is also more than sufficient for the demand. If problems occur when connecting sensors to this module, it is worth knowing that you also have the possibility to connect current signals to the NI 9205 module if you install a 500Ω resistance between the signal cables.

The last module, NI 9401, is made for digital I/O signals and has 8 bidirectional channels. It has three configurations: 8 digital inputs, 8 digital outputs or 4 digital inputs and 4 digital outputs. The sensor needing a digital input module is the rotational speed sensor, so the 8 digital inputs or the 4 of each configurations can used.

As Nepal, from time to time has a very unstable grid, all the DAQ devices should be connected with equipment providing stable voltage to avoid damage. In addition, sensors should have fuses at voltage supply cables.

4.1.2 Sensors

4.1.2.1 Flow sensor

There are two different flow meters at TTL, KU. One has been used at the simplified turbine test rig and is manufactured by ISOIL. The other one was ordered for another test set-up, but was never used and is still brand new. This is made by Kometer. The flow meter from ISOIL has less uncertainty, so it is recommended to use this.

The ISOIL MS2500-E200-A7A2A has an opening with 200 mm diameter. Normally, the straight sections upstream and downstream of the sensor should be respectively three and two times as long as the sensor diameter. Since the piping is 400 mm in diameter, cones towards the sensor is needed. The general rule with three and two times the diameter, is then too little in this case, since ISOIL recommends maximum 8° cone angle.

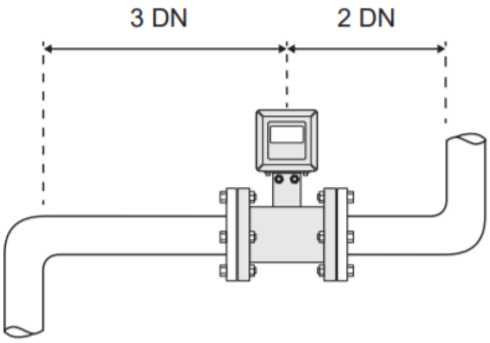


Figure 4.3: General rule for pipes upstream/downstream the sensor [35].

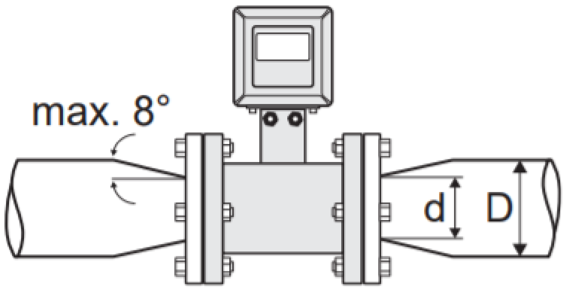


Figure 4.4: When cones are used, ISOIL recommend max. 8 ˚cone angle. With a pipe diameter >> sensor diameter, this will be the leading parameter to follow [35].

4.1.2.2 Torque, friction torque and axial thrust sensor

How the torque, friction torque and axial thrust will be measured is still a work in progress. How this is done can be seen in Morten Grefstads master thesis [9]. So far, it has been decided to use a HBM T40B torque flange. This is a sensor based on strain gages and provides analog signals between ± 10 V. The torque flange also have a digital output for rotational speed.

Figure 4.5: Torque flange HBM T40B with rotational speed sensor. Both signals are to be used at TTL, KU. Photo: HBM.

4.1.2.3 Rotational speed sensor

The rotational speed sensor is a built into the HBM T40B torque flange and consist of a slotted disc with 108 holes. The sensor sends a digital signal every time a light is passing through a hole in the disk. This is used to calculate the rotational speed in LabVIEW.

4.1.2.4 Pressure sensors

As shown in chapter 3.4, the only pressure used directly in the formula for the efficiency is the differential pressure over the turbine. For this, you can use gauge pressure sensors, one at the inlet and one at the outlet of the turbine. Indirectly, you also need an atmospheric pressure sensor to find the mean absolute pressure in the turbine. This, together with the water temperature, is used to calculate the right density for the water. The gauge sensors already exists in the lab and are made by Omega. The atmospheric sensor similar to the gauge pressure sensor will be ordered from Omega.

Figure 4.6: Omega PXM319 gauge pressure sensor with mini DIN connection will be used at TTL, KU [37].

When measuring the gauge pressure in a pipe cross-section, the best measurements are done by having four pressure taps evenly distributed around the pipe and connect them to a shared manifold. To avoid air to aggregate in the manifold, no tap should be at the top of the pipe. You can either choose a ring manifold, or choose a straight manifold and connect each pressure tap with a transparent tube to the straight manifold. If the last option is chosen, the transparent tubes should be equally long and slope up towards the manifold.

If you choose one or another option, every pressure tap should have its own valve to measure the pressure at individual positions. In addition, a gas-collecting chamber with a valve to flush out the air should be at the highest point of the manifold. A drain vent should also be close to the sensor to get rid of air bubbles aggregated in the tube from the sensor. In addition, the sensor opening should point upwards to avoid having air bubbles getting stuck in the sensor opening. At this point, Figure 4.7 can be a bit misleading, as the sensors that will be used at TTL looks different from the picture in IEC 60103 [1].

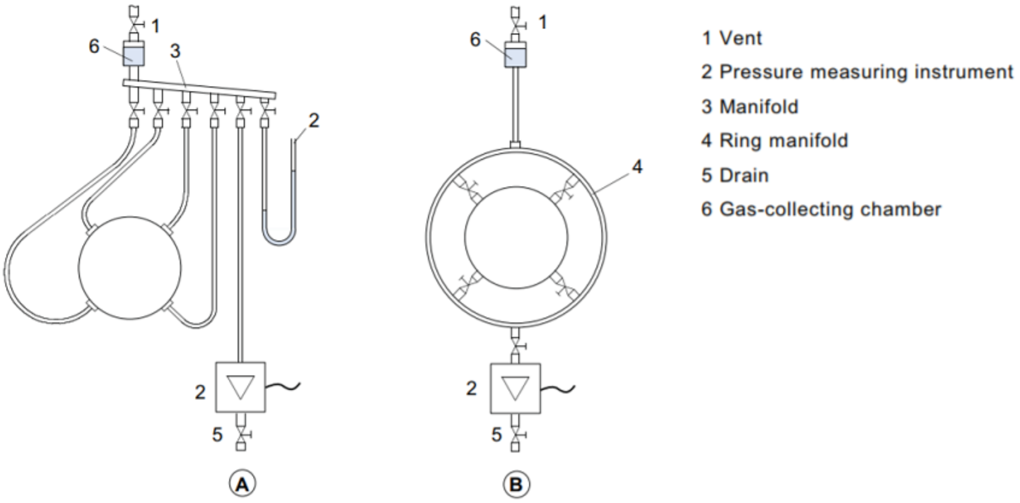


Figure 4.7: Two options for connecting the pressure taps together [3]. A) Straight manifold with transparent tubes. B) Ring manifold.

The pressure taps should have a sharp or slightly rounded edges towards the inside of the pipe as shown in Figure 4.8.

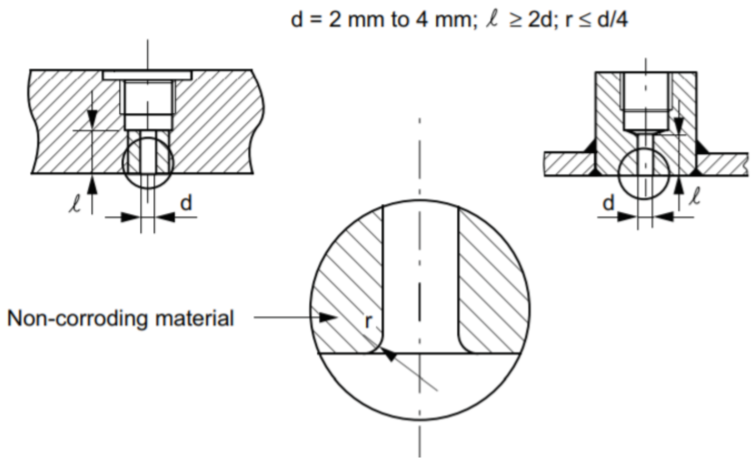


Figure 4.8: Design of pressure taps according to IEC 60193 [3].

To make the calculations for density, absolute pressures and head as easy as possible, the recommended sensor set-up will be like explained in chapter 3.4. That means to have the gauge pressure sensors at the same level as the center of the inlet and outlet pipe and the atmospheric pressure sensor somewhere in between, preferably in the middle.

4.1.2.5 Guide vane angle sensor

The recommended sensor for TTL is the same model that the Waterpower Laboratory at NTNU just bought. As the sensor measure the guide vane angle digitally, it may not need calibration. It depends on how the manufacturer has planned the installation process for the sensor and TTL will have to look into this later. The sensor converts the measurement into an analog output, which makes the programming easier in LabVIEW. As the sensor is mounted on one of the guide vane axles, make sure that the variation in the position of the different guide vanes is taken into account when calculating the uncertainty.

4.1.2.6 Temperature and oxygen level sensor

The temperature sensor at TTL will be used when calculating the density of the water. When the writer visited TTL in April and May, there were some problems connecting the sensors already existing in the laboratory to the DAQ system. Since it was difficult for the researchers at TTL to find the brand and model name for the sensor, it was also difficult to know what kind of technology the sensor used. It has later been found that it is a PT100 sensor, which uses RTD technology. As of now, it looks like documentation, brand and so on is missing and programming it in LabVIEW can be difficult. Also, it is important to know the brand/model name to be able to document the uncertainty for the sensor. If it is not found, it is recommended to buy a new one. Depending on which kind of connections the sensor have, it can be set up differently as mentioned in chapter 3.2.7. If the more basic 2-wire methods are used, it can be smart to keep the wires between the sensor and DAQ as short as possible, due to inner resistance in the wire leads to deviations in the results. TTL will have to look into this at a later occasion.

To measure the oxygen level, the same sensor which is used at NTNU should be purchased. This will have to be connected with a transmitter of the same brand as the sensor.

4.1.3 Avoiding noise

“Ensuring measurement accuracy often means going beyond reading raw specifications in a data sheet. Understanding an application in the context of its electrical environment is also important for securing success, particularly in a noisy or industrial setting. [30]”, NI states at their web page. Even though noise usually is something that occur in heavy industrial places with lots of high voltage and rotating equipment, it may appear in laboratories like TTL as well, if not considered in advance. This especially apply when you want a trustworthy and high-precision result from a test. The most important things to consider is mentioned in this chapter, but it is recommended to have someone with more advanced skills within electronics to have a look at the test set-up as well.

First of all, the acquisition devices should be placed in a cabinet a bit away from generators, pumps and high voltage sources.

Secondly, the signal wiring should be properly shielded and placed in wire fixtures all the way to the cabinet. High voltage cables should not be installed in the same fixture as the signal wiring.

Thirdly, if signal wires are crossing high voltage cables on the way to the cabinet, they should cross perpendicular to avoid disturbance.

Fourthly, since there sometimes is a difference in earth and neutral, all the equipment should be grounded thoroughly.

4.2 Control system

First, it was decided that LabVIEW only was going to be used for monitoring and not for controlling the test rig. After various meetings with the people working with the development of TTL and phone calls to the different system manufacturers, there was a turnaround on this subject. Apparently, National Instruments has added functions for connecting PLCs to the LabVIEW software. Thus, it was decided late in May that the control system of the test rig should be programmed in LabVIEW as well.

One does not want the measuring system and the control system to inflict each other, and to avoid this a new DAQ unit, modules and a new computer should be ordered for the control system as well. One of the components that will be used in this system is the Linak LA35 actuator. This will be used for controlling the guide vanes on the test rig. It has both a digital input and two sets of equivalent outputs, one digital and one with current output. Other equipment that will be connected to the control system will be the main pumps, the pressure tank pump, the draft tube pump, the generator and different valves around the pipe system.

4.3 The LabVIEW logging system

To solve various demands, the logging system has been made flexible with lots of control options. The program monitors almost all values that directly concern the efficiency test. It will log data from all analog instruments connected to the DAQ unit, in addition to the digital rotational speed sensor on the new Francis test rig at Kathmandu University. By doing this, more sensors can be connected to the test rig, which allows for further analyses if a model test show unexpected efficiency measurements. Even though all sensors are implemented to the program, some modifications might be needed to get the right results. Especially, the friction torque and the axial torque may not be working properly, due to unfinished design/sensor set-up.

The logging system has been programmed in continuous mode as mentioned in chapter 3.5. It will monitor the sensors continuously, regardless of whether the logging is activated or not. When the logging is activated, it will continue for a preset time and the file will save all the readings within this interval. Since it is not set to log a specific number of readings, it may, at a very few occasions, differ slightly from one operational point to another for the analog channels. If this happens, the number of readings will typically differ with number of samples the program read per channel per iteration. As a default, this is preset to 1000. The number of the rotational speed readings can, on the other hand, differ a lot, since it is calculated from a set of digital signals that increase proportionally with the runners rpm.

4.3.1 The Front Panel

The Front Panel is strongly inspired by the logging program used at NTNU, but has one extra tab. Hence, the VI has four tabs in the Front Panel, described with their respective functions here:

1. File settings: Change location folder for saving and change file name.
2. DAQ settings: This tab has three sub-tabs depending on what kind of input signal you have - one for voltage, one for current and one for digital signals. Under all tabs, the operator can change channel name, sensor brand/model, sensor serial number, specify connection port and insert calibration constants for the instrumentation. Special for the voltage and the current tabs is that you can set input terminal configuration. The right

choice in this control depends on how you connect the wires to the sensors. The voltage is now preset to differential and the current signals are preset to default. Special for the digital tab is that you can set the terminal channel. This is used for counters and timers and are often used together with digital signals.

3. Logging: Controls for g, A_1, A_2, D and Δz_M. The default value set for the gravity is found from the formula in *IEC 60193* [1] and the calculation can be seen in appendix D. The geometry settings and height difference between the sensors has some test values set as default. These must be changed before using the program at TTL. On the same tab, there are indicators showing H_e, n, Q_{ED}, n_{ED}, η_h and α in real time. Waveform charts are also made for the most used values when logging efficiency. In the middle of the screen – a button to start the logging, a control for changing desired logging time and an indicator showing how long it has lasted. There is also a control to change the name of the specific operational point that is logged. The guide vane angle and n_{ED} are, for example, good choices to explain which operational point you are logging. That way, it will be easier to find and organize the data retrospect to the testing. As this tab is the one the operator will us the most, the stop button for the program is also found here.
4. Monitoring: Showing other useful sensor data in waveform charts.

4.3.2 The Block Diagram

The Block Diagram is a little bit more intricate piece of programming and should only be reprogrammed by people that has competence similar to what is taught in the NI tutorial Core 1 (v2015). This master thesis and the manual in appendix C should also be read properly to understand the approach that has been used for making the program. The logging program at NTNU has been an inspiration for some of the subVIs in the Block Diagram, but most of the code is programmed quite different. The reason for this is that the program at NTNU is relatively difficult to understand and the writers intention was to make a program that was easy to understand, even for students, but yet have advanced and flexible functions.

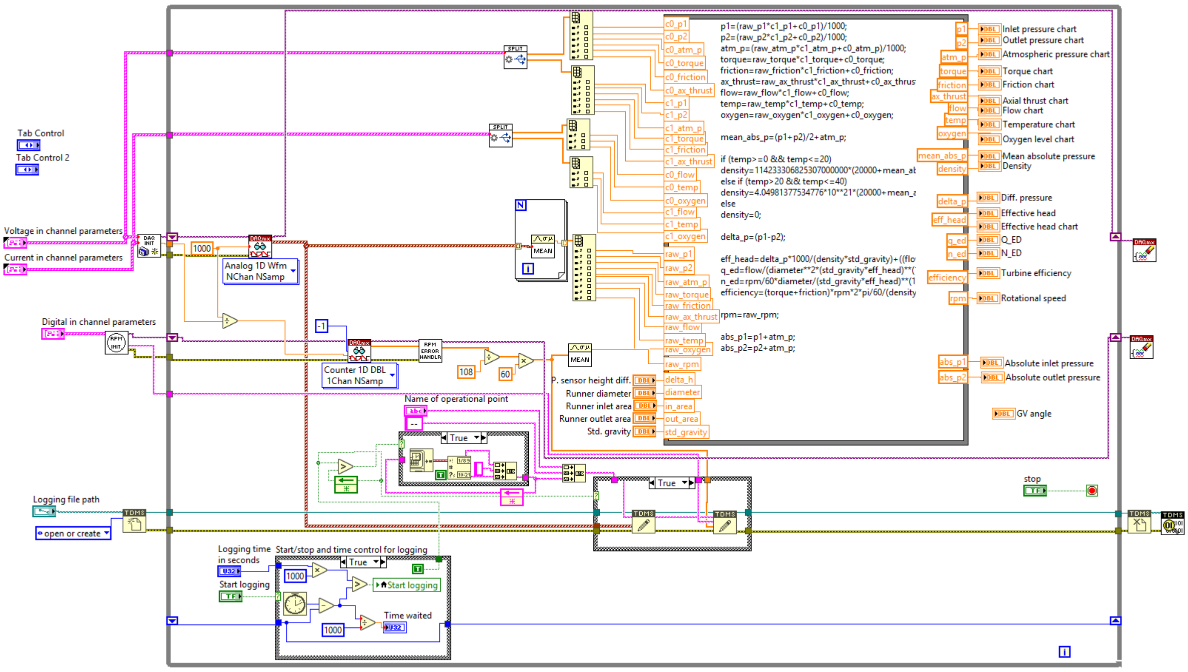


Figure 4.9: The block diagram of the logging program made for TTL, KU.

The main component of the program is the While Loop, making the program to run until the stop button is pushed. The While Loop, together with different DAQmx functions, are the most important building blocks in making a continuous program. The DAQmx functions will be explained in the chapters on subVIs later in the text. The functions and information on the outside of the left border of the loop are only executed when the program starts, and hence saves your computer for reading many functions every time the While Loop iterates. Because of this, it is important to remember that the program must be stopped for evaluating changes done to for example logging file path, sensor names, sensor constants or physical channel paths. The functions at the right side of the loop are mostly clean up and close functions, which executes after the programs stop button has been pushed.

The functions inside the While Loop can roughly be assigned to two main objectives. The middle and upper right part of the loop works with monitoring data, while the lower left part is working with the logging. The Formula Node is used to process most of the data monitored in the Front Panel. The inputs of the Formula Node is different constants and mean data from the DAQmx read functions.

The lower left corner of the While Loop has three Case Structures. These are all controlled by a boolean value where 1 means that the true case should run and 0 means that the false case should run. All cases are indirectly controlled by the start logging button. The first case structure is the one on the bottom of Figure 4.10. For each iteration where the start button has not been pushed, this case structure check the clock and send the time value from one iteration to the next through a Shift Register. It also send a false value out from the Case Structure. If the start logging button is pushed, the Case Structure calculate the time between the current time value and the last time value it got from the Shift Register. As long as the desired logging time is bigger than the calculated time, the Case Structure send out a true value. First, this value is sent to a greater than function and a corresponding Feedback Node. The Feedback Node works similar to a Shift Register. It keeps the value from the last iteration. This way, the greater than function will only send out a true value the first iteration with a value of 1.

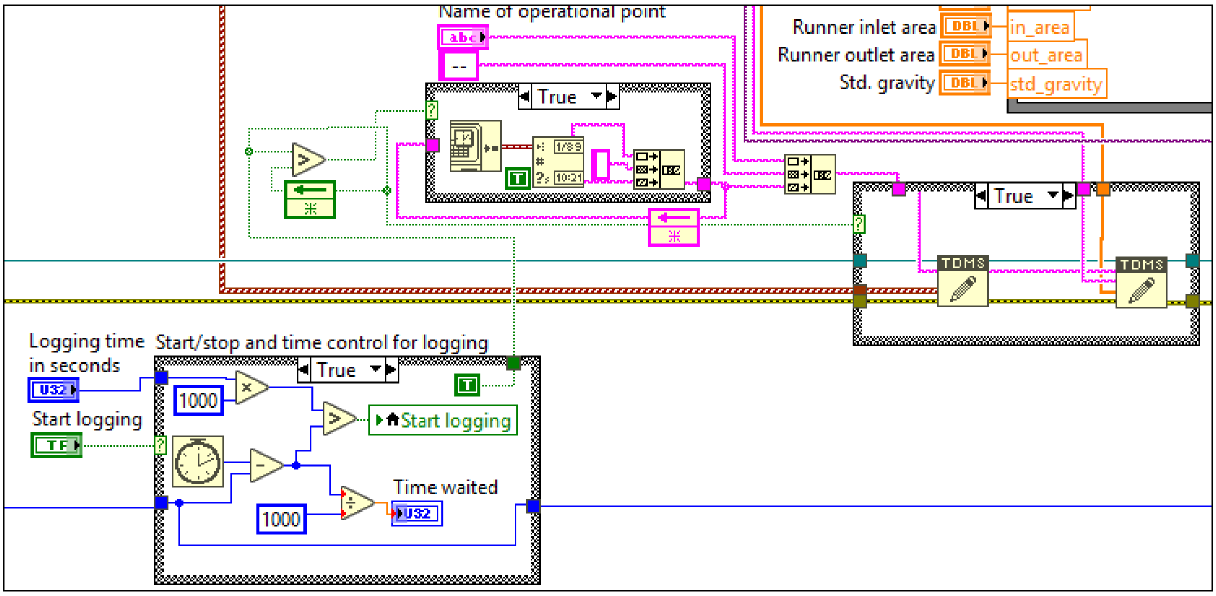


Figure 4.10: Case structures found in the block diagram of the logging program for TTL. Used for different logging functions.

The true value is then sent to the Case Structure adding time and date to names for operational points or group names, as LabVIEW calls them. This Case Structure also has a corresponding Feedback Node. This makes the case structure use the same time and date as soon as it reaches the second iteration. This name function is made to avert the operator in deleting previously logged operational points. If he or she had forgot to change the name, without having the function for adding time and date, the TDMS function would think that the desired action is to overwrite the samples with the same group name. Not for every iteration, but for every time you start a new logging. It seems like the TDMS Write function have some kind of feedback, knowing that it shall keep the same group name through the whole logging sequence. The true value from the first case structure is going directly to the last case structure where the TDMS Write functions are, skipping the greater than function.

4.3.2.1 The “DAQ init analog KU” subVI and corresponding DAQmx Read function

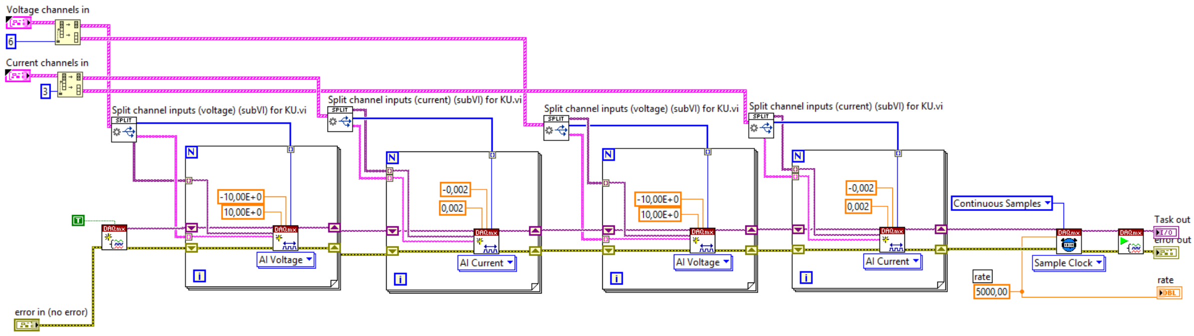


Figure 4.11: The subVI called "DAQ init analog KU".

The “DAQ init analog KU” subVI is basically telling the DAQmx read function in the while loop what, how and in which order it shall process the analog channels. To log the samples from the different channels, two For Loops would be sufficient – one for voltage and one for current. Since the samples also is going to be processed in the Formula Node before monitoring, it was important to let the sensors used for efficiency to be read first. That way the operator can add as many new sensors to the program as he like without destroying the calculations. This could have been fixed with one voltage and one current DAQ initiation subVI programs, but this would also add more mean functions, TDMS File functions and so on to the While Loop. The Block Diagram in the logging program looks cleaner and is easier to understand the way it is programmed now. The blue DAQmx function at the right side of Figure 4.11 is called DAQmx Timing. This is set to Sample Clock for analog channels and let you choose the continuous sample mode and the rate at which the DAQmx will collect samples from the sensors. As a default, this has been set to 5000 samples per second per channel.

Back in the Block Diagram of the main VI, the DAQmx task is sent in through the While Loop and to the DAQmx Read function. This is set for analog samples and will read 1000 samples per iteration. With the rate of 5000 samples per second, every loop iteration will take 0.2 seconds. Make sure to check in the manuals if sensors manage to update the out signals as quickly as the sample rate.

4.3.2.2 The “RPM init KU” subVI, the corresponding DAQmx Read function and the “RPM Error Handler”

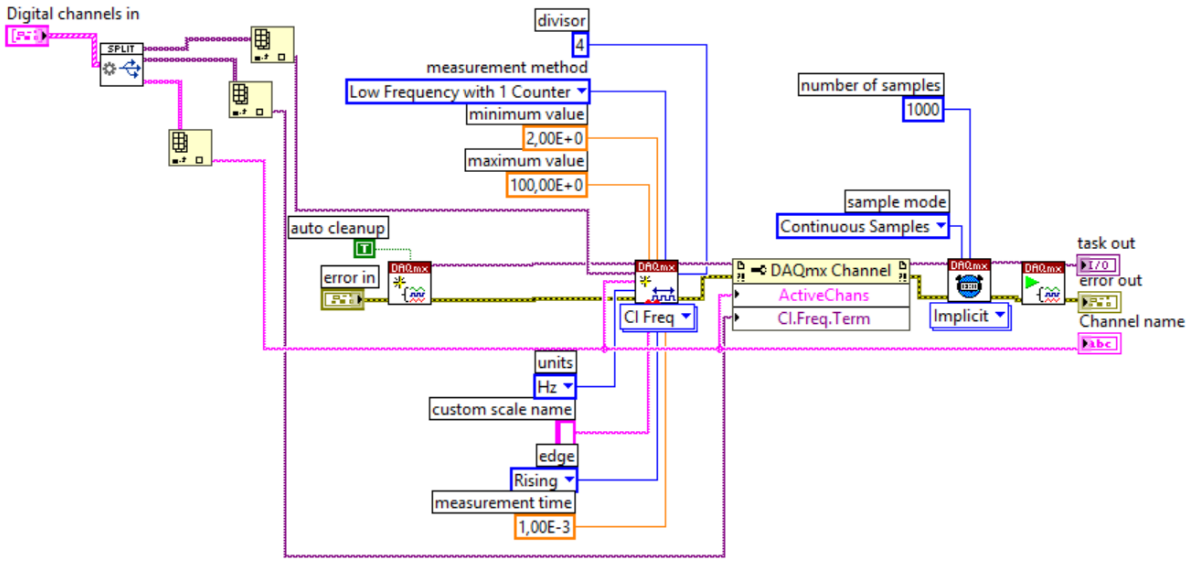


Figure 4.12: The subVI called "RPM init KU".

The initialization subVI for rotational speed is built a little bit different from the subVI for the analog channels. Since rotational speed is a function of time, the “Digital channels in” cluster is splitted into two DAQmx wires. One is for the physical channel where the digital pulses are measured and one is for the terminal inside the DAQ unit that is used for counting the time between the digital pulses. The DAQmx functions use this to find the frequency in Hz, which later is calculated into rpm. Also, mark that the DAQmx Timing is set to Implicit instead of Sample Clock, which is better for counter tasks.

Back in the While Loop, the DAQmx task is sent from the subVI to the DAQmx Read function which is set to Counter. Since the amount of signals acquired from the sensor will vary with the rotational speed, the number of samples is set to -1. The -1 tells the DAQmx Read function to acquire all available samples instead of a specific number of samples. If the number of samples had been set to 1000, as it is programmed for the analog sensors, it would have had a problem acquiring enough samples. This would slow down the iteration time to manage to acquire enough rpm samples, making the program buffer to fill up with analog samples. The program has been tested with number of samples put to -1 and much higher rotational speeds than what is used for Francis turbines, but even then the counter does not manage to acquire too many samples per iteration. That means that the buffer neither will fill up with rpm samples or analog samples and the program will run smoothly.

The ”RPM Error Handler” subVI is not an advanced program as no errors occur and the logging program is running as desired when tested at low and high rotational speeds. The subVI is built around a Case Structure where the different error codes decide which case to run. The error code 0 is the default and means no error. No other error codes have been added yet since no other codes was detected during tests. The only function it is has now, is that it sends out value 0 instead of NaN when the rotational speed is zero or near zero. The subVI is mostly made for showing how errors can be handled if future problems occur in the logging program when it is used at TTL, KU.

5 Conclusion

This report explains how to perform model tests on Francis turbines, in addition to describe the laboratories at the Norwegian University of Science and Technology and Kathmandu University. Some of the descriptions are general, but most of them focus on sensor and acquisition equipment and technology. When analyzing the sensors at NTNU, the calibration methods were also illuminated. Further on, the report point out recommendations for sensors and acquisition systems that should be used for the Francis test rig at the Turbine Testing Lab, Kathmandu University. An advanced, but yet simple LabVIEW program has been made for steady state testing, which among other things can be used to log measurements regarding turbine efficiency. The report also include a detailed walk through of the programming technics and functions used for the logging program. The expectation is that the students and the employees at TTL can use the report as a guide when they implement sensors to their system or want to reprogram the logging program. By finishing this report and the logging program, the Turbine Testing Laboratory at Kathmandu University has finished another big step towards being certified by the *IEC 60193* [1] standard.

6 Further work

This chapter includes recommendations for further programming in LabVIEW. Some of the work is needed to have a fully operative logging program, but most of the recommendations are mostly to add user friendly functions in the program and to ease the processing of data after testing.

Need to be done

Program LabVIEW to:

- Work properly with the axial torque/friction torque system made by Morten Grefstad. Can most certainly be used as it is if Mortens result is one sensor for each measurement and the output of the sensors are in volts.
- Monitor tank level and Thoma number. This must be done when the system design is finished.

Recommended, but not required to be done

Program LabVIEW to:

- Make a data file with a table with mean values from every group name. This should be a button operated function that can be used when the logging is completed. This will save the operator a lot of time when he or she is making hill diagrams in MATLAB later on.
- Have a function for deleting a set of readings from the logging file – typically chosen by the group name.
- Add a note to each group name. Can be used for making comments about each operational point. For example “Unstable RPM”.
- Add standard deviation/uncertainty to the program.
- Make new programs for logging various sensor calibrations and producing calibration reports. Some of the calibration programs used at NTNU may be used directly.

A. List of sensors at NTNU

Sensors at NTNU

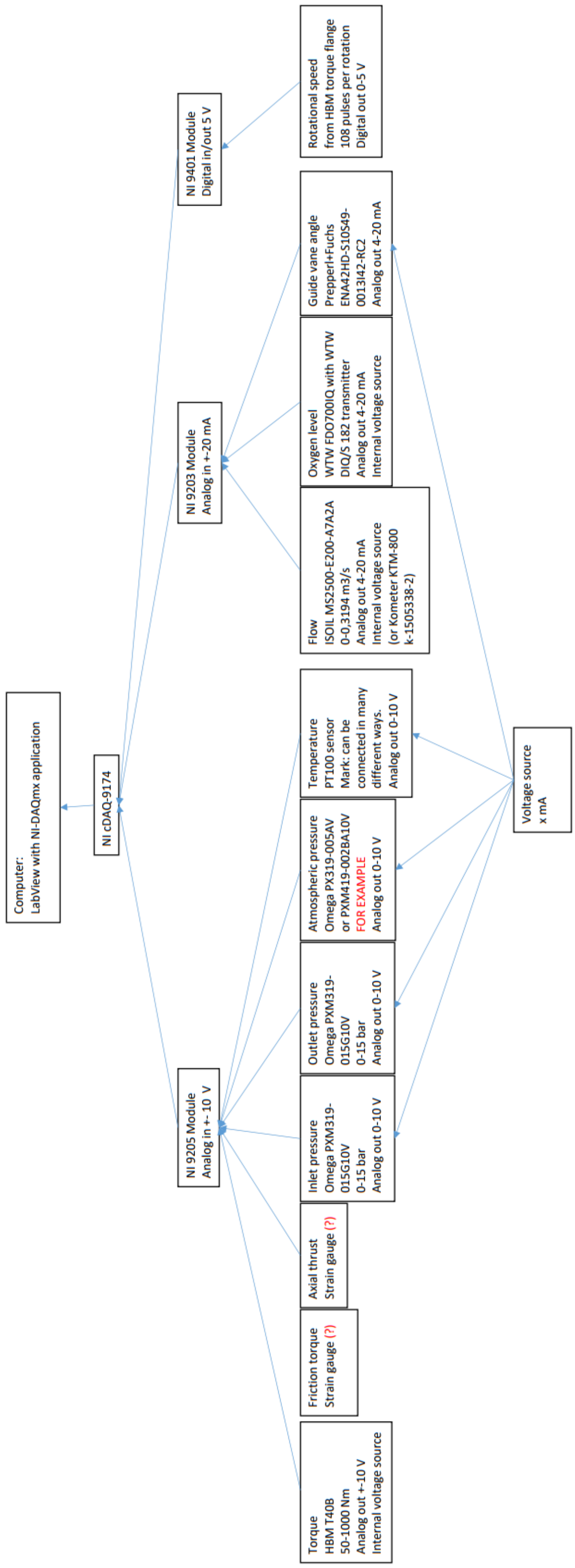
What kind of sensor	Need external voltage source?*	Signal type from sensor to DAQ	Model name	Specifications
Pressure (diff. pressure and inlet)	Yes	4-20 mA	Fuji Electronics FHCW36W1-AKCAY	Range limit (-50)-50 bar Span limit 5-50 bar
Pressure (atmospheric)	Yes	4-20 mA	GE PTX5072-TB-A3-CA-HO-PA	0-5 bar (absolute)
Torque	Yes	+/- 10 V	HBM Z6FC3	500kg
Friction	Yes	+/- 10 V	HBM Z6FC3	10kg
RPM	Yes	Digital	Custom/self-made	One pulse per rotation
Flow	No	4-20 mA	Krohne Altometer IFS 4000/6 with Krohne Altometer SC 100 AS transmitter	DN250mm
Temp	Yes	0-10 V	Some kind of PT100	Mark: can be connected in many different ways.
Axial Thrust	Yes	4-20 mA	Fuji Electronics FKCW*4V4AKCYYAE	Range limit (-100)-100 bar Span limit 1-100 bar
Oxygen	No	4-20 mA	WTW FDO7001Q with WTW DIQ/S 182 transmitter	
Guide vane angle	Yes	4-20 mA	Prepperl+Fuchs ENA42HD-S10S49-0013I42-RC2	(Just ordered - not installed in lab yet)

*Some measurement equipment have voltage source inside sensor or transmitter

Important! Remember that the torque, friction and axial torque measurements will be quite different at KU compared to NTNU.

Also, know that even though many of the sensors have current outputs, they are usually connected to the NI 9205 voltage module with a resistance instead. With a 500Ω resistance between the signal wires the output signal transforms from 4-20mA to 2-10V.

B. Dataflowdiagram KU



Important! Know that even though some of the sensors have current outputs, they are can be connected to the NI 9205 voltage module with a resistance instead. With a 500Ω resistance between the signal wires the output signal transforms from 4-20mA to 2-10V.

C. Manual for the logging program

Open the LabVIEW Project named "Logging program KU Project- TTL" and make sure that all the files in LabVIEW Project Explorer are in the project folder "your_destination/Logging program TTL" in File Explorer at your computer.

Before running the program

1) Make sure all sensors are working, and connected correctly. You can easily check if the sensors are providing signals in the program NI MAX.
2) Press the folder button, choose a file path and write a new logging file name. Optionally, choose an old logging file. If you choose an old file, the program will keep the old readings in the file and ad the new readings at the end.
3) In the DAQ settings tab, pull and expand the tables if more sensors are needed. For the sensors you need, press the buttons so they become green and say "IN USE". All sensors which are in use will be logged.
4) Make sure the right calibration constants, DAQmx physical channel, input terminal configuration (apply for voltage/current channels) and DAQmx terminal (apply for digital channels) are set.
5) IMPORTANT: Do not change the order of the first 7 voltage channels, first 3 current channels and the first digital channels, as this will affect the calculations in the monitoring part of the program.

While running the program

1) Make sure standard gravity and geometry specifications are correct.
2) Set the time you would like to log
3) Set a name for the specific reading. For example, guide vane angle and n_{ED}. If you forget to change the name between two readings, it is no problem, since the program also will add the time and date to the group name.
4) When you are finished logging for the day, it is beneficial to stop the program with the stop button in the logging tab, as this will open a window with quick view of all the measurements in the file.

Before closing the program

1) If you are going to use the same test set-up with the same calibration constants and geometry specifications the next time you run the program, it is beneficial to save the values you have inserted in the tables. This can be done by pressing the "Edit" tab and then press "Make Current Values Default".

D. Standard gravity calculation for TTL

The standard gravity set as default in the LabVIEW program is calculated from the formula in *IEC 60193* [1]:

$$g = 9.7803 \cdot (1 + 0.0053 \cdot \sin^2 \varphi) - 3 \cdot 10^{-6} \cdot z$$

Where
φ is the latitude in degrees, and
z is the altitude in meters.

The latitude for TTL was found from GPS coordinates:

$$\varphi = 27.62°$$

The mean altitude was also found from GPS coordinates, using the altitudes of the approx. position of the upper and lower reservoir. Then the mean altitude was calculated:

$$z = \frac{1514.0 + 1487.4}{2} = 1500.7\, masl$$

Used in the formula for standard gravity, giving:

$$g = 9.7803 \cdot (1 + 0.0053 \cdot \sin^2(27.62) - 3 \cdot 10^{-6} \cdot 1500.7 = 9.7869\ \frac{m}{s^2}$$

E. MATLAB Scripts

Scripts from Morten Grefstad project thesis [31].

E.1. Hill diagram code

```
%Graphics
% Create figure
figure1 = figure('Name','HillDiagram');

% Create axes
axes1 = axes('Parent',figure1,...
    'Color',[0.894117653369904 0.941176474094391 0.901960790157318],...
    'ZColor',[0 0 0],...
    'YMinorTick','on',...
    'YColor',[0 0 0],...
    'XMinorTick','on',...
    'XColor',[0 0 0]);
%% Uncomment the following line to preserve the X-limits of the axes
xlim(axes1,[0.148 0.222]);
%% Uncomment the following line to preserve the Y-limits of the axes
ylim(axes1,[0.050 0.230]);
hold(axes1,'on');

% Create plot
plot(n_ED(:,8),Q_ED(:,8),'DisplayName','\alpha=14.5','Marker','*');

% Create plot
plot(n_ED(:,7),Q_ED(:,7),'DisplayName','\alpha=13.0','Marker','o');

% Create plot
plot(n_ED(:,6),Q_ED(:,6),'DisplayName','\alpha=11.5','Marker','x');

% Create plot
plot(n_ED(:,5),Q_ED(:,5),'DisplayName','\alpha=10.0','Marker','^');

% Create plot
plot(n_ED(:,4),Q_ED(:,4),'DisplayName','\alpha=
8.5','Marker','pentagram');

% Create plot
plot(n_ED(:,3),Q_ED(:,3),'DisplayName','\alpha=  7.0','Marker','+');

% Create plot
plot(n_ED(:,2),Q_ED(:,2),'DisplayName','\alpha=  5.5','Marker','v');

% Create plot
plot(n_ED(:,1),Q_ED(:,1),'DisplayName','\alpha=  4.0','Marker','diamond');

%% Testing the addition of Efficiency curves in the plot
% contourLevels = [95.5 95 94.5 94 93.5 93 92.5 92 91.5 91 90.5 90];
% contour(n_ED,Q_ED,Eta,contourLevels,'LineColor','k');
%
%[EtaMax, idx] = max(Eta(:));
```

```
%n_ED_EtaMax = n_ED(idx);
%Q_ED_EtaMax = Q_ED(idx);
%loglog(n_ED_EtaMax,Q_ED_EtaMax,'rs','MarkerSize',8,'DisplayName','*\eta');
%% Create xlabel
xlabel({'Dimensionless speed n_E_D [-]'},'FontSize',11);

% Create ylabel
ylabel({'Dimensionless flow Q_E_D [-]'});

% Create title
title('Hill Diagram');

% Create legend
legend1 = legend(axes1,'show');
set(legend1,...
    'Position',[0.814534927681696 0.737769369968863 0.0565476183557794
0.141829389707403]);


%% Kode mottatt fra tidligere arbeider, for HILL-linjene
%Området som skal plottes for Ned
fontSizeLabel=14; fontSizeAxes=14; fontweight='bold';

NN=100; x=linspace(0.148, 0.222, NN); %generer en vektor med NN punkter
mellom linespace(X,Y
n=zeros(NN,8); q=n; e=n;


for i=1:num_alpha
    q(:,i)=interp1(n_ED(:,i), Q_ED(:,i), x,'cubic','extrap'); %Ned mot Qed
(med ekstrapolasjon)
    e(:,i)=interp1(n_ED(:,i), Eta(:,i),x,'cubic','extrap');  %Ned mot etta
end

N=zeros(NN,NN); Q=N; E=Q;

for i=1:NN
    N(:,i)=x;
    Q(i,:)=linspace(0.05, 0.230, NN); %Området Qed skal plottes for
    E(i,:)=interp1(q(i,:), e(i,:), Q(i,:),'cubic','extrap');
end

% Lager hilldiagram-linjene
contourLevels=[95.2 95.1 95 94.5 94 93.5 93 92 91 90 88 86 84 80 76];
figure(1);
[C,h]=contour(N, Q, E, contourLevels); %Contour(limit1,limit2,det som skal
plottes, antall linjer def av vektor str)
set(h,'LineStyle','-','LineColor','k')
clabel(C, h, 'manual','fontSize' , fontSizeLabel, 'fontWeight', fontweight)
```

E.2. Efficiency diagram code

```
%% Graphics
% Create figure
figure2 = figure('Name','HillDiagram2');
```

```
% Create axes
axes2 = axes('Parent',figure2,...
    'Color',[0.894117653369904 0.941176474094391 0.901960790157318],...
    'ZColor',[0 0 0],...
    'YMinorTick','on',...
    'YColor',[0 0 0],...
    'XMinorTick','on',...
    'XColor',[0 0 0]);
%% Uncomment the following line to preserve the X-limits of the axes
xlim(axes2,[0.148 0.222]);
%% Uncomment the following line to preserve the Y-limits of the axes
%ylim(axes2,[0 0.25]);
hold(axes2,'on');

% Create plot
plot(n_ED(:,8),Eta(:,8),'DisplayName','\alpha=14.5','Marker','*');

% Create plot
plot(n_ED(:,7),Eta(:,7),'DisplayName','\alpha=13.0','Marker','o');

% Create plot
plot(n_ED(:,6),Eta(:,6),'DisplayName','\alpha=11.5','Marker','x');

% Create plot
plot(n_ED(:,5),Eta(:,5),'DisplayName','\alpha=10.0','Marker','^');

% Create plot
plot(n_ED(:,4),Eta(:,4),'DisplayName','\alpha=  8.5','Marker','pentagram');

% Create plot
plot(n_ED(:,3),Eta(:,3),'DisplayName','\alpha=  7.0','Marker','+');

% Create plot
plot(n_ED(:,2),Eta(:,2),'DisplayName','\alpha=  5.5','Marker','v');

% Create plot
plot(n_ED(:,1),Eta(:,1),'DisplayName','\alpha=  4.0','Marker','diamond');

% Marking the point with highest efficiency
%loglog(n_ED_EtaMax,EtaMax,'rs','MarkerSize',8,'DisplayName','*\eta');

% Create xlabel
xlabel({'Dimensionless speed n_E_D [-]'},'FontSize',11);

% Create ylabel
ylabel({'Efficiency [%]'});

% Create title
title('Efficiency vs n_E_D');

% Create legend
legend1 = legend(axes2,'show');
set(legend1,...
    'Position',[0.779657049008749 0.624096385542169 0.0691605185588186
0.272566931017113]);
```

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