Lastområdesutvidgning med aktiv flödeskontroll i Francisturbiner

Expanding operation ranges using active flow control in Francis turbines

Sebastian Adolfsson

Acknowledgements

I want to thank all personnel at Jämtkraft that has been very helpful and provided with experiences and information about their facilities. Also I want to thank my handlers Michel Cervantes at LTU[1], Talib Morad at UMU[2] and Peter Palmqvist at Jämtkraft for the aid they have provided with.

I want to thank Knut Magne Olsen, technical chief at Troms Kraft who has been very helpful and given a well guided tour at Skibotn power plant. I also thank Torbjørn Kristian Nielsen for the study visit at NTNU[3].

For technical information I want to show special gratitude towards Håkon Francke at FDB[4] that has shared and allowed presentation of his test results and extensive knowledge about the water injection technique.

I thank Patrick March at HPP[5] Inc for allowing presentation of his graphical findings regarding aeration techniques and efficiency.

For allowing publication of research material I thank Smith Brennan T, Sabin Mathew, Jo Magnus Solberg, Patrick March and Håkon Francke.

I also thank Henrik Lindsjö at Andritz Hydro and Urban Andersson at Alstom for discussions and practical perspectives on ae ration techniques.

For economic information I show large gratitude towards Morten Kjeldsen at FDB for making an economic estimate of installing the peripheral water injection system at the case study.

Sammanfattning

Denna rapport innehåller en undersökning av fluidinjiceringstekniker för att reducera skadliga flödeseffekter i sugröret hos Francisturbiner som arbetar utanför optimal last. Det finns ett fokus på implementerbarhet hos Jämtkrafts anläggningar och två vattenkraftverk har undersökts som är placerade i serie med varandra vid namnen Lövhöjden och Älviken. Det enda lönsamma scenariot som upptäcktes med en viss grad av säkerhet var en ökning av lastområdet uppåt för att tillåta överlast.

Upptäckter visade att både luft och vatten kan införas på olika platser för att förbättra hydraulisk verkningsgrad kring turbinens delar såväl som att reducera tryckpulsationer i skadliga lastområden. Investeringar i sådana system har visat sig vara användbara och lönsamma på flera platser med dåligt anpassade manövreringsvillkor. Men på grund av förluster i effektivitet då injektionssystem körs visar det sig olönsamt i situationer där de inte förbättrar lastområdet på ett sådant vis att det resulterar i ökad årlig eller topp-produktion.

Abstract

This report contains an investigation of fluid injection techniques used in the purpose of reducing deleterious flow effects occurring in the draft tube of Francis turbines when operating outside nominal load. There is a focus on implement ability at Jämtkrafts hydroelectric power plants and two power plants were investigated, located in series with each other named Lövhöjden and Ålviken. The only profitable scenario found with some degree of certainty was an increase in the operating range upwards to allow overload operation.

Findings show that both air and water can be introduced in various locations to improve hydraulic efficiency around the turbine parts as well as reduce pressure pulsations in harmful operating regions. Investments in such systems have proven useful and profitable at several facilities with poorly adapted operating conditions. But due to losses in efficiency when operating injection systems, it turns out unprofitable in situations where it does not improve the operating range in a way that is resulting in increased annual or peak production.

.

Table of contents

Nomenclature

Following physical quantities are mentioned in the report; they are explained individually in the text

$P = Power \left[\dfrac{kgm^2}{s^3}\right]$

$\tau = Torque \left[\dfrac{kgm^2}{s^2}\right]$

$p = Pressure \left[\dfrac{kg}{ms^2}\right]$

$\rho = Density \left[\dfrac{kg}{m^3}\right]$

$g = Gravitational\ acceleration \left[\dfrac{m}{s^2}\right]$

$v = Velocity \left[\dfrac{m}{s}\right]$

$\dot{m} = Mass\ flow \left[\dfrac{kg}{s}\right]$

$z = Elevation\ [m]$

$R, r = Radius\ [m]$

$t = Time\ [s]$

$C_e = Cost\ of\ energy$

$\eta = Efficiency$

Following abbreviations are used in the report

$BEP = Best\ Efficiency\ Point$

$STD = Standard\ deviation$

$DO = Dissolved\ Oxygen$

$FFT = Fast\ Fourier\ Transform$

$MAMSL = Meters\ Above\ Main\ Sea\ Level$

1 Introduction

Today hydropower acts as an important part of the Nordic electrical grid due to capabilities of storing fuel and varying production of both active and reactive power. The ability to sell regulating power is becoming increasingly desirable with establishment of the north European power market NORDPOOL together with development in intermittent power production sources. Investments to increase power production in facilities using renewable resources are also eligible to receive electricity certificates in the EU, a factor that increases incentives to invest in hydropower drastically.

Most hydropower plants equipped with reaction turbines, especially Francis, are only able to produce power within a limited operational range around BEP[6] of the turbine. Undesired operational modes usually exist due to the occurrence of deleterious flow effects in the turbine runner and draft tube when operating at part loads. These effects are mainly pressure surges due the draft tube geometry and residual swirl in the flow entering the draft tube. The residual swirl is due to mismatch in angular momentum provided by the guide vanes and the angular momentum extracted by the turbine, resulting in uneven mass transfer of water to its surrounding structure. Some periodic fluctuations even risk falling inside the resonance frequencies of the water system, leading to so called hydro-acoustic resonance, causing hazardously large vibrational amplitudes.

Water flows needed to maintain the rivers in accordance with water-rights judgments or to maintain downstream reservoirs are often so low that they fall outside the acceptable operational range of the turbine. This can lead so scenarios where water is spilled pass the turbine without utilizing it for power production. Also a normal production scheme is to run a facility at max efficiency during peak hours and stop it at lower price periods in order to maximize the extracted profit from water reservoirs, a scenario in which the equipment may suffer many and harmful annual start and stop cycles.

Countermeasures can be made to reduce destructive flow effects, resulting in increased plant availability that in turn reduces conflicts of interest in power production planning and reliability viewpoints. In some cases it is possible to increase the annual power production at a hydropower facility by being able to utilize smaller flows then originally designed for. Many countermeasures include physical inserts in the draft tube or turbine, something that risks having a negative impact on the turbine efficiency at BEP.

This study is focusing on the investigation of two techniques where fluid is injected in the draft tube flow in order to reduce the pressure surge phenomena's. Water and air are the working fluids in these systems and even with consideration to their differences they have both been proven to produce positive results and can both be turned off to operate at BEP. Pay-back times of these investments has in the most successful case been a few months, but most facilities are too small to make a noticeable profit or have already solved the operational range problem by installing several turbines in parallel or are using turbines with extended operating range.

The goal is to attain knowledge about implement ability and profitable scenarios related to these techniques at hydropower stations owned by the job requestor. Also a presentation of the problems present at the undesired operating modes of the Francis turbine should be made. Information is gathered via research of literacy and company documentation as well as from adepts within the field. Results show a good degree of overall system implement ability and an operating environment with low economic incentives at all enquired facilities.

---

[6] Best Efficiency Point

2 Aim

The aim of the project is to make an economic and technical investigation of two fluid injection techniques. The fluids injected will be air and water which will have different effects, system structure, investment costs, planned installation time and technical properties.

A case study shall be made at Lövhöjden, an 8,5MW plant with 99m water head, annual production of 24GWh and is owned and operated by Jämtkraft. The goal is to appreciate the technical implement ability and economic environment surrounding the investment of both the water and air injection systems.

3 Method and sources

3.1 Air injection

A literacy study and discussions with adepts at Alstom and Andritz Hydro will act as the fundament for the theoretical understanding of the air injection system.

H. Lindsjö at Andritz Hydro is consulted to make an economic estimate of the installation costs of an atmospheric air injection system at the case study.

3.2 Water injection

The theoretical understanding will be built from literacy research, meetings with adepts at NTNU and FDB. Also a visit is made to Skibotn, a 72MW facility owned and operated by Statkraft, utilizing the water injection system. At FDB H. Francke provides with results from the systems and M. Kjeldsen is consulted for an estimate of the installation costs at the case study.

4 Structure

The report starts with a theoretical introduction of turbine equipment, its related problems and a description of countermeasures to these problems as well as a description of a certain case study. Following the theory is a results chapter which consists of technical and economic summaries of the air and water injection systems separately, referring to results from several documented scenarios. The results chapter ends with the case study findings. The report is finished with an analytical discussion about attained results and further research.

5 Theory

This section concerns some basic theory surrounding the investigated phenomena's and techniques. It is presented to give a general understanding of the key factors.

5.1 Francis turbine

The Francis turbine is the most commonly used turbine in hydropower plants globally and can be designed to utilize a large range of water heads with high efficiency. Most Francis turbines suffer a common problem related to pressure surges in the draft tube occurring around half load and operating at these loads is therefore avoided. To explain the Francis turbine makeup, a short review of its parts is presented below. They are presented in the same order as water is passing through the turbine. A cut through picture is seen in Figure 5-1

Penstock – Provides pressure potential and flow of water to the spiral casing. Pressure is exerted by the weight of the above water head.

- Spiral Casing – Surrounding the runner with spiral geometry of area decreasing with its length, this is to maintain uniform velocity to the stay vanes. This structure is housing the stay and guide vanes that are spatially distributed around the runner in the center.

- Stay vanes – Fixed fins that convert pressure potential to kinetic energy and are reducing swirl of the inlet flow by aligning the direction of the flow towards the runner section.

- Guide vanes – Movable fins that are used to regulate flow rate and the angle of attack to the runner. These are connected in a circular structure called a wicket gate, which can be moved hydraulically to change their position simultaneously.

- Runner – Converts kinetic energy and pressure potential energy in the water to torque transferred by the shaft. Water enters radially and leaves axially exerting both impulse and lift force to the runner blades.

- Draft tube – Connects to the runner outlet and converts kinetic energy to pressure potential due to a diffusing geometry meaning an area increasing along its length.

- Shaft – Connecting the turbine runner and generator rotor and is transferring the torque extracted by the runner from the water. This part is not characteristic for the Francis turbine but can due to its sometimes hollow structure be used as an air path when injecting air and is due to the nature of this report mentioned here.
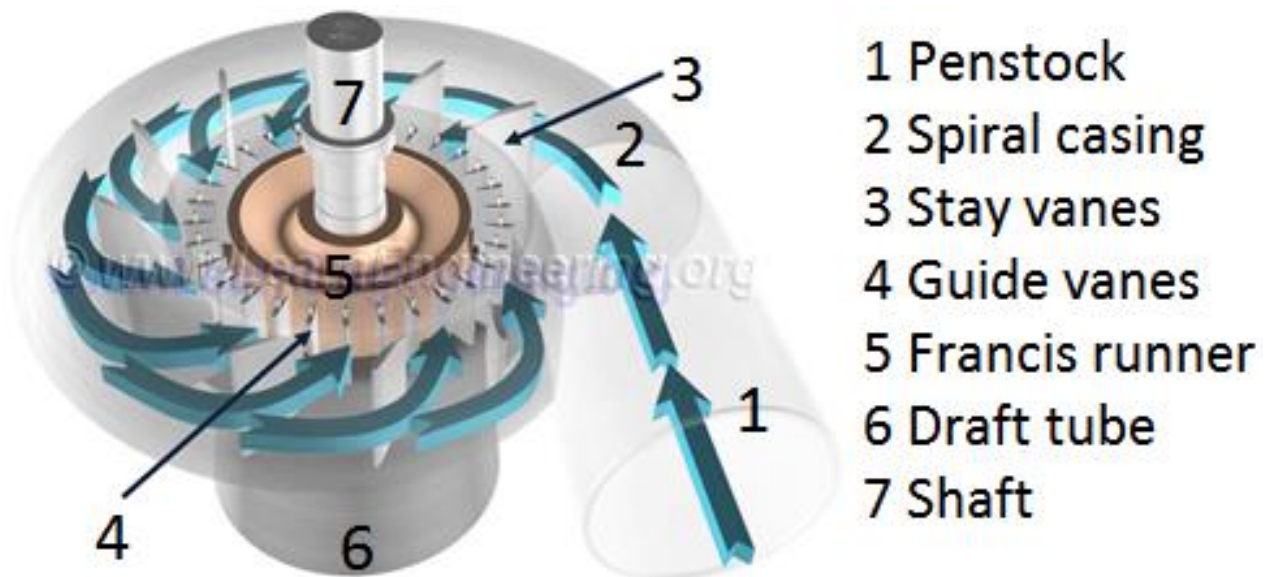

1 Penstock
2 Spiral casing
3 Stay vanes
4 Guide vanes
5 Francis runner
6 Draft tube
7 Shaft

Figure 5-1 – Francis turbine [1]

When water is leaving the turbine operating at BEP and enters the draft tube, its velocity profile should ideally consist only of an axial and no angular component. When the turbine is operated in part or over load modes the swirl generated by the wicket gate in the spiral casing is not matching the angular momentum extracted by the runner, hence leaving a residual rotational velocity component at

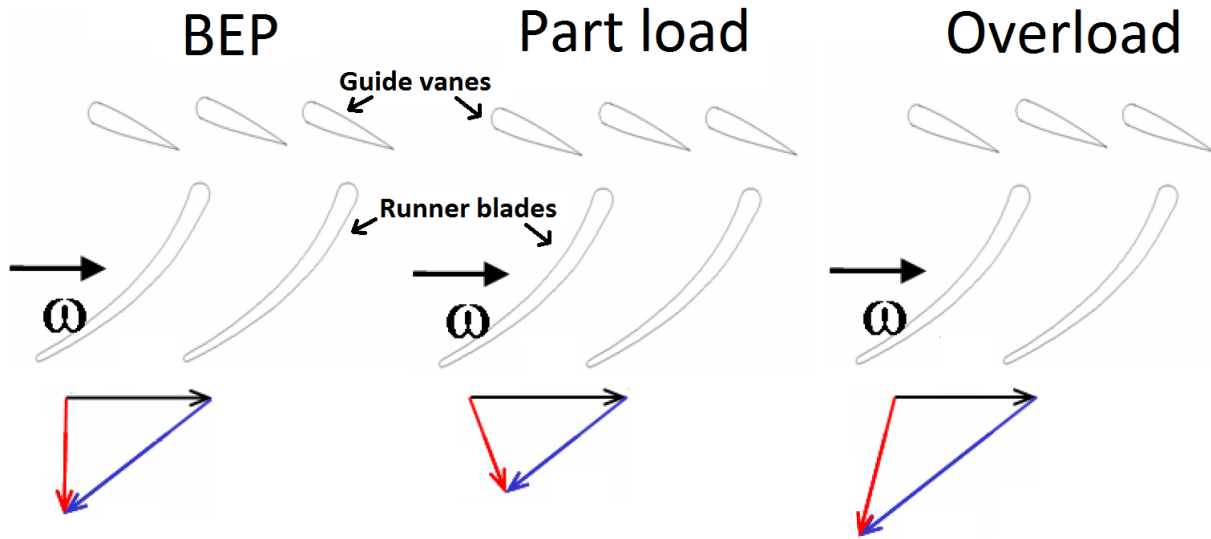the runner outlet. Direction of water flow leaving the runner is depicted by the red vector in Figure 5-2.

Figure 5-2 – Velocity distribution for water leaving Francis runner at BEP, Part load and Overload

The residual swirling velocity is thought to be the cause of severe pressure surges in the draft tube and it is noted that at part loads the swirling flow is rotating in the same direction as the runner and at over load the swirl is rotating in the opposite direction of the runner.

Difference in pressure at runner and guide vanes varies with the difference in water head over the turbine. Power plants with large head variation may suffer operational problems due to the difficulties in designing a turbine runner that can handle the different operating regimes sufficiently.

5.2 General flow characteristics

A general understanding of the relation between pressure, elevation and velocity in a fluid flow can be achieved by studying a simple one dimensional version of Bernoulli's principle as presented below

$$\frac{v^2}{2} + gz + \frac{p}{\rho} = constant$$

v is relative velocity in a control region $[\frac{m}{s}]$

g is gravitational acceleration $[\frac{m}{s^2}]$

z is elevation $[m]$

p is pressure in the control region $[\frac{kg}{ms^2}]$

ρ is density $[\frac{kg}{m^3}]$

The equation is expressing continuity of enthalpy in the flow where the effect from changing each variable easily can be mirrored into the others. The inverse relation between pressure and velocity is of most importance when studying flow behavior since it can give a simple understanding of effects such as cavitation and pressure pulsations.

It should be noted that the Bernoulli expression above is valid for laminar flows and the flows discussed in this report is turbulent patterns and breakdown of these into less structured turbulent flows.

Using Darcy-Weisbach equation for turbulent flow the only addition is a decrease in the relation between pressure loss and velocity relative to the decreased in wall friction as velocity and Reynolds number increases.

A dimensionless number used to describe the amount of swirl present in the flow is the so called swirl number S, which is defined as the ratio between angular and axial momentum in the studied boundary as depicted below. The axial velocity profile of the draft tube flow at runner exit for different swirl numbers is depicted in Figure 5-3 below.
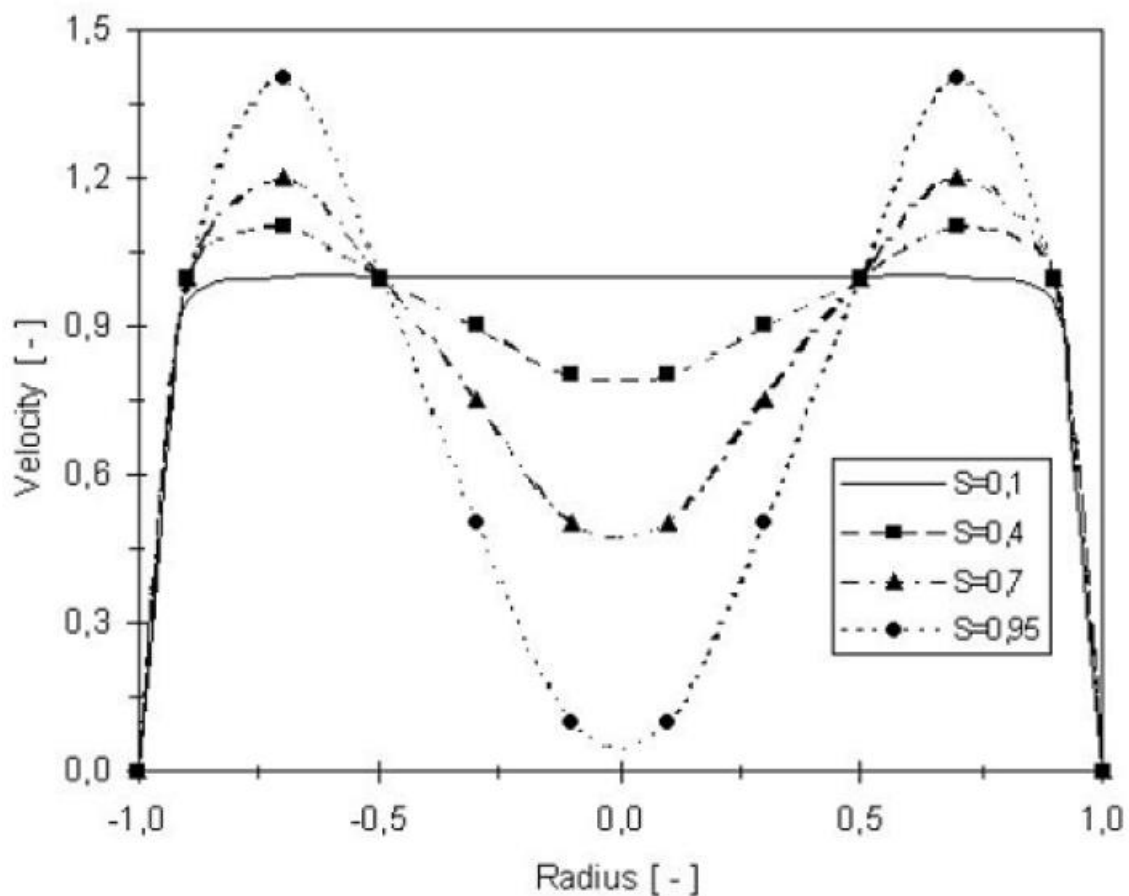
$$S = \frac{Angular\ momentum}{Axial\ momentum}$$

Figure 5-3 – Expected axial velocity profiles in the draft tube at different swirl numbers [2]

An increase in the swirling velocity component will result in increased axial velocity around the draft tube edges and a reduction in axial velocity at the center of the tube.

In swirling flows the velocity relative to the surrounding fluid can become very high and if recirculation starts to occur in the central region of the flow, the water at the boundaries of this region experiences very large differences in relative velocity which results in a drastic decrease in pressure.

5.3   Deleterious flow effects

Pressure surges are normally divided into synchronous and asynchronous types, both of these types can cause effects in the flow which might show harmful to the plant infrastructure. The effect believed to be most harmful and mainly responsible for the draft tube pressure surges are named vortex breakdown and vortex rope, these are discussed in this section and are depicted in Figure 5-4 below.

Figure 5-4 –Low part load, normal part load, high part load and overload draft tube vortices

Pressure surges can propagate through the whole hydraulic system and even cause pressure and head variations in the penstock. Some problems associated with draft tube surges include severe vibrations, noise, power swings, bearing and shaft run-out, and increased stress on the runner.

Although it should be noted that statistical investigation covering 34 low head Francis runners manufactured the years 1928-1967 with heads between 20m to 80m shows that the number of yearly starts and stops together with the height of water head has the strongest negative correlation to the turbine lifetime. [**3**]

This suggests that the start stop problem is more prominent and that it is not only desirable to decrease pressure pulsations at part loads in order to increase the permissible operating range. But it can also be interesting in cases where it is possible to decrease the number of yearly start and stop cycles as a result of the extended operating range.

5.3.1   Vortex breakdown

As the swirl increases to a critical level, a sudden change of the flow characteristics can be observed. Namely a reverse flow starts in the stalled center region, see Figure 5-3. A helical vortex will form at edges of this reverse flow region. In this boundary the pressure can decrease to vapor pressure, causing evaporation. The water gas bubbles will make the vortex visible and when such a flow structure occur the phenomena is called vortex breakdown. See Figure 5-4

It should also be mentioned that the axial velocity of the water flow usually is depicted as a steady profile with non-changing vector sizes. When recirculating flow occurs there is a discontinuous break in the velocity profile, called boundary layer separation.

As the flow continues along the positive pressure gradient in the draft tube, the vortex is gradually loosing kinetic energy until the cavitated core condenses and the vortex dissolves into turbulent flow in almost all cases. When the cavitated bubbles collapse to liquid there is a resulting pressure pulse.

Some flow patterns can be termed regular and some irregular. Laminar flow and synchronous flow patterns can then be seen as regular. As turbulent and unstable flow patterns can be seen as irregular. A depicted test setup using dye injection to picture a helical vortex flow pattern is seen in Figure 5-5.
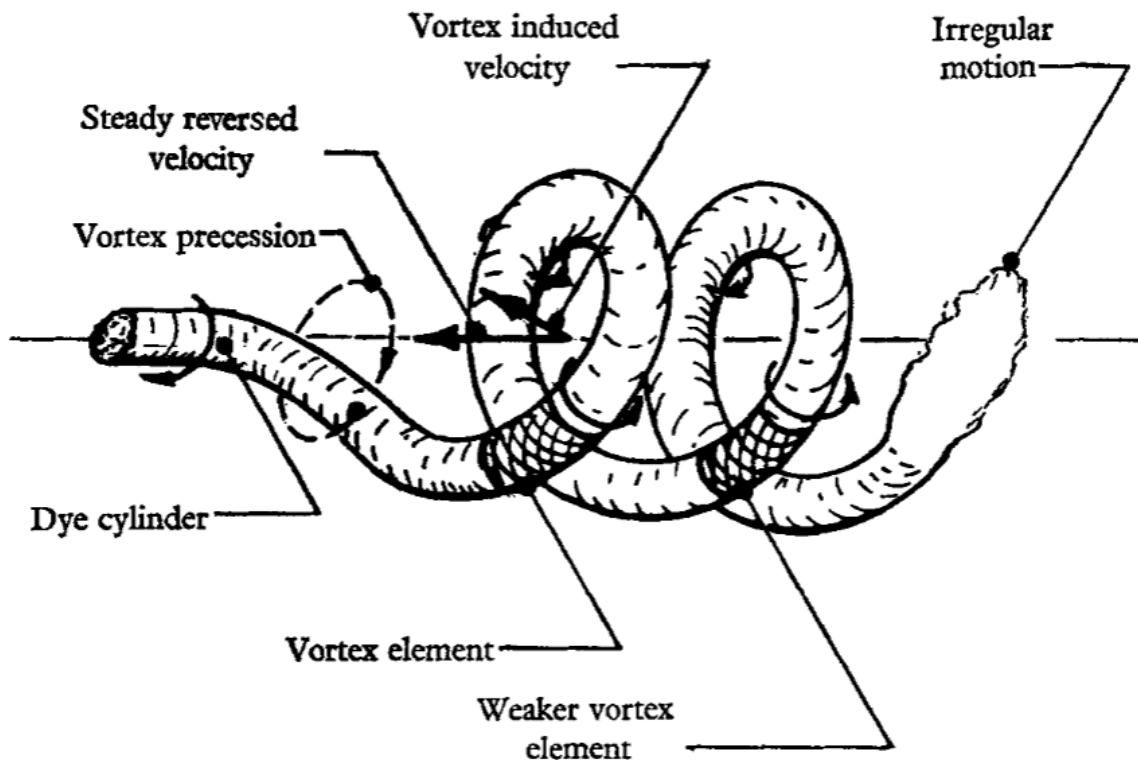

Figure 5-5 – Vortex breakdown [2]

5.3.2 Vortex rope

This flow pattern is the most severe cause of efficiency reduction and pressure fluctuations experienced by most Francis turbines at part load. These fluctuations can in extreme cases even propagate to the electrical grid due to the oscillating pressure experienced by the runner. This is more prominent in facilities that have a considerably small amount of rotational mass.

The residual swirling component left in the flow due to off design operation of Francis turbines is entering the expanding and often non-conical geometry of the draft tube. This is causing uneven pressure increase as well as velocity decrease in the flow, resulting in a change in the rotational axis of the swirl. This gives as a result a helically precessing vortex rope, such as depicted in Figure 5-6.

This vortex rope is rotating at the so called Rheingans frequency, which is found to be in the region of about ¼-½ of the runner frequency but is empirically found to be $\frac{1}{3.6}$ of the runner frequency. [4] Any stationary point in this region of the draft tube will experience uneven mass transfer and pressure pulsations as the vortex rope rotates, see Figure 5-7.

This flow pattern is quite robust and is rotating uniformly and regularly. At the limits of the range of its occurrence it can however become intermittent as neighboring flow patterns become prevalent. [5]

The length of the cavitated core is related to flow speed and when the cavitated vortex core or parts of it implodes, sharp pressure shocks are produced. This happens in flow regions between two different flow patterns which can occur at different loads in the draft tube as the velocity and pressure changes along its length.
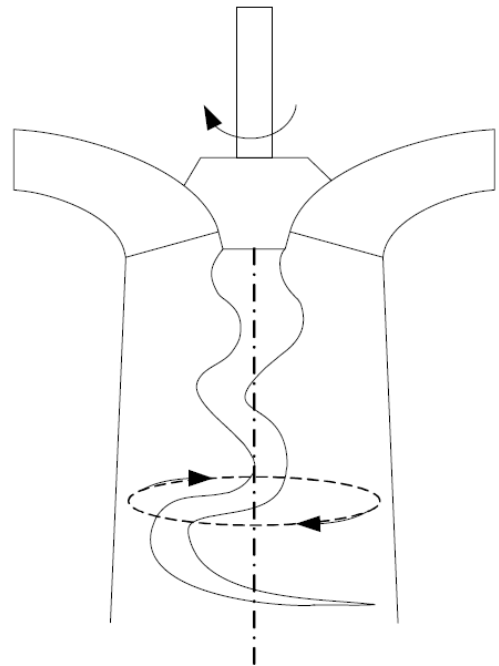

Figure 5-6 – Draft tube vortex rope at part load

This vortex has received many names such as helical vortex, spiral vortex, corkscrew vortex and the term vortex rope which is used in this report. The rotating motion around its axis has been termed the precession of the vortex. [6]
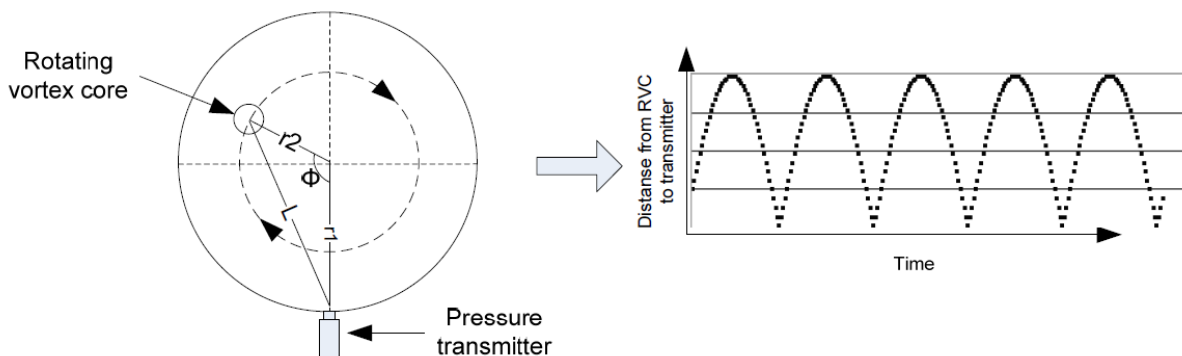

Figure 5-7 – Pressure signal from rotating vortex core at a fixed point in the draft tube

5.3.3 Hydro acoustic resonance

All structures in nature resonate at a certain frequency and can be associated with springs whose resonant frequency is depending on its mass and stiffness/rigidity. Just as potential energy and kinetic energy is exchanged between each other in the oscillating motion of a spring is the potential and kinetic energy within a material structure is exchanged between each other in a periodic manner as it oscillates. This exchange will result in positive interference if oscillating forces are in phase with each other in the systems characteristic frequency. This causes amplification of the oscillation amplitudes and something that becomes highly undesirable in the maintenance and reliability point of view.

The resonance frequencies of the water way system is usually quite low, somewhere between a few Hertz to a few tens of Hertz and in most cases lower then 200Hz. The frequency of the so called water hammer phenomena is related to the length between two free water surfaces and the propagation speed of acoustic waves in the water as in the manner expressed below:

$$f_{wh} = \frac{a}{2L}$$

a is the acoustic propagation velocity

L is the length between two free water surfaces

The Rheingans frequency usually has the largest pressure amplitude in the hazardous frequency range but pulses that are tuned with the resonance frequency will not need high amplitudes to cause severe vibrational swings.

The following frequencies are commonly found in relation to Francis turbines: [7]

Runner frequency: $f_n = \frac{n}{60} [Hz]$

Runner blade frequency: $f_b = f_n * z_b [Hz]$

Guide vane frequency: $f_g = f_n * z_g [Hz]$

Rheingans frequency: $\frac{f_n}{4} \leq f_r \leq \frac{f_n}{2} [Hz]$

n is the runner rotation speed

z_b is the number of runner blades

z_g is the number of guide vanes

It is believed that higher frequencies that is originating from the runner often is suppressed by the dynamics of the vortex rope and Rheingans frequency is the most prominent frequency related to the draft tube surge. Even though the wake flow between rotor blades and guide vanes and the draft tube surge exist at different locations and is usually viewed as separate phenomena, they are likely to influence each other. [8]

It has also been stated that the pulsation of the overload vortex is corresponding to one of natural frequencies of the water way system [9]

5.4 Countermeasures

In this section the theory related to countermeasures is investigated. The air and water injection technique is in focus and it should be mentioned that both systems can be operated in such ways that they cause additional problems instead of reducing them. However, a great advantage in comparison to fixed structure inserts as a countermeasure.is their adjust ability. Making it possible to tune the systems to each operating point and shut them off when desired. Countermeasures can be categorized either as passive or active depending on energy expenditure and the existence of a control loop.

5.4.1 Air injection

As will be seen in the next section regarding other countermeasures, there has been various techniques tested to reduce the impact of the draft tube pressure pulsation and air admission is one of the most commonly used of these. A turbine is delivered with a rated operating range and air injection will usually be implemented if it is required in order to meet delivery agreements.

Air will mitigate to the low pressure zones in the flow, drastically changing the pressure dynamics in the flow along its path. The air path is mainly determined by the flow speed and the location of aeration points. Air can be introduced at several locations, both above and below the cavitation zone of the runner and can either be ejected using compressors or sucked from the atmosphere by the low draft tube pressure. Figure 5-8 depicts some possible admission locations of air.
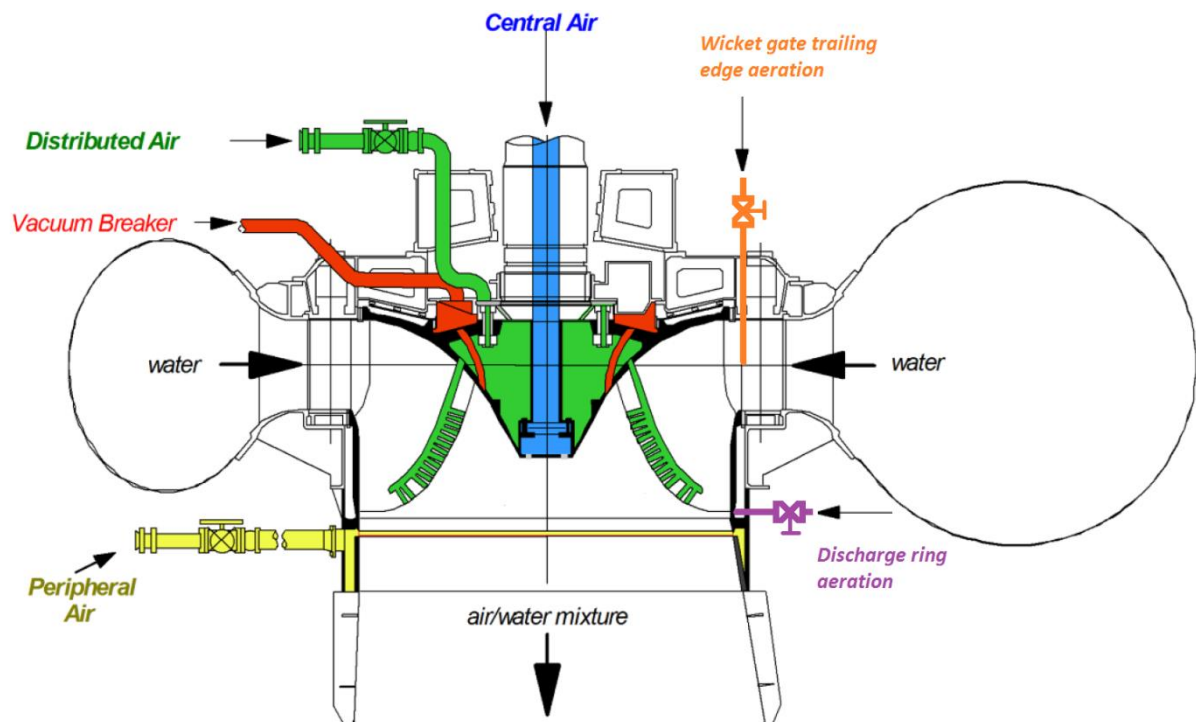

Figure 5-8 – Section view of Francis turbine with different aeration techniques shown [10]

When injecting air into the draft tube flow the resulting air/water mixture will have a dramatically reduced dispersion speed of longitudinal compression/decompression waves; i.e. pressure pulsations. These waves are of the same nature as sound waves and since the harmonic content and the amplitudes of studied draft tube flow phenomena fall outside the definition of sound, the notation acoustic waves are used.

The reduced propagation speed of acoustic waves occurs mainly since the mixture inherits properties of compressibility from the air and density from water. It is also conceivable to deduct that the

temperature in the mixture will deviate slightly when introducing air, however the influence of the thermal properties of the mixtures on the wave propagation speed is neglect ably small in comparison to the mechanical properties.

Dangerous frequencies that can exist in the working fluid are the ones coinciding with the natural frequencies of the water system and the materials in contact with it. Pressure pulsations of these frequencies are critical to avoid in a maintenance and reliability point of view and can both be induced and reduced using air injection.

Special aerating turbines have been developed due to the environmental interest of maintaining aquatic habitats by increasing levels of DO[7] in the water. This need is strongest in warmer regions and the turbines are designed to minimize efficiency losses due to the air injected, the loss in efficiency is however considerable large in most cases.

Aeration can also be made through check valves mounted at the draft tube periphery, this aeration technique mainly concerns problems with DO but may due to its simple installation procedure provide with an easy solution in some special flow problems. [**11**]

In general, a air injection system normally consists of the following parts seen in Table 5-1 [**10**]

Air Intake	Designed intakes to reduce pressure losses and noise levels at the intake, typically bell mouths Properly designed intake can be used for air flow measurements
Air Flow Instrumentation	A variety of technologies are available, some examples are Venturi meters, Orifice plates, Pitot static tubes, Hot-film anemometers, Bell mouth inlets, Calibrated elbow meters with velocity measurements And depending on the air flow meter selected it might be complemented with Manometers, Thermometers, Barometers and/or Hygrometers Type of instrumentation is depending on the intension of the system
Sound Mufflers	Designed noise dampers to reduce noise to a safe level without decreasing the air flow significantly
Control Valves	Valves used to regulate the air flow, these may be operated manually, remotely or by a control system
Air Supply Piping	Structural air paths to the aeration points. Vacuum breaker systems usually have too narrow air paths for supplying enough air flow. The shaft is in many cases hollow and can be used as a good air path, usually through the generator
Check valves	Used for unidirectional flow, some check valves that can be used are Ball check valves, Lift check valves, In line check valves and Swing or tilt check valves
Control system	Computer system monitoring air flow and regulates control valves.
Injection holes	Designed holes or nozzles at the injection points that usually is either in the spiral casing, the draft tube, the runner blades trailing edge, the runner cone or in an aeration ring mounted on the runner

Table 5-1 – Typical air injection system components

---

[7] Dissolved Oxygen

Table 5-2 shows physical quantities of interest when evaluating aeration systems, separated into performance aspects.

Mechanical performance	Hydraulic performance	Environmental performance
Turbine efficiency	Aeration-influenced efficiency change	Change in DO uptake
Maximum power output		Total dissolved gas TDG
Cavitation levels	Airflow	Other water quality parameters
Vibration	Pressure at aeration outlets	Airflow
Shaft run-out		
Thrust load		

Table 5-2 – Measureable performance aspects of interest when evaluating aeration systems

Air introduced in the runner can most easily be taken from the bearing gallery and through the shaft and generator. Peripheral air can be supplied from the machine room where the draft tube is mounted. In Figure 5-9 is a picture of air inlets used for distributed aeration mounted in the bearing gallery.
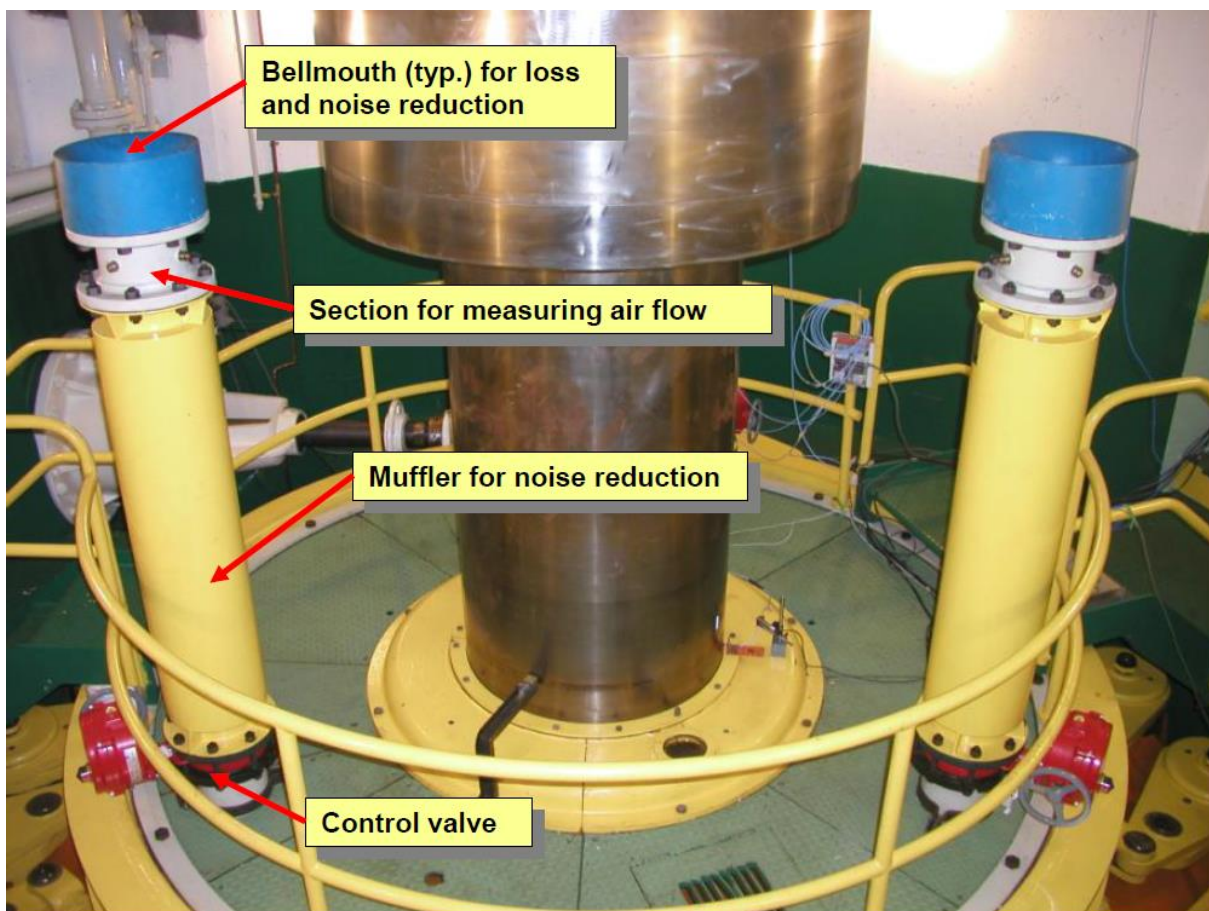

Figure 5-9 –Francis distributed aeration system inlet, bearing gallery [10], [12]

Escudier, M states that the air injection at the center of the recirculating region will produce a stable axis-symmetric flow with an air core surrounded by the swirling water; this is the blue path in Figure 5-8. Air injection is said to change the breakdown form from a spiral to a bubble. [**13**]

Central air injection results in a quick efficiency reduction with increased air flow, the technique with least efficiency losses attributed is distributed aeration followed by peripheral aeration. [**12**] More is presented about this in the results section.

5.4.2 Water injection

Injecting water as a countermeasure to the draft tube swirl is a relatively new method but several solutions already exist. It can become efficiency neutral due to the increase in draft tube and runner efficiencies counteracting the losses due to water bypassing the turbine blades. Systems where water is injected through the runner cone and draft tube walls has been found [**13**] and this study focuses on the latter of these.

The water injection system focused on in this report has been installed at Skibotn power plan, Owned and operated by Troms Kraft Produksjon. This system is developed by M. Kjeldsen and uses specific flow rates through nozzles that are mounted at the draft tube walls. They are mounted at a horizontal and vertical angle to the draft tube and are located at a distance from the runner, as depicted in Figure 5-11 below.
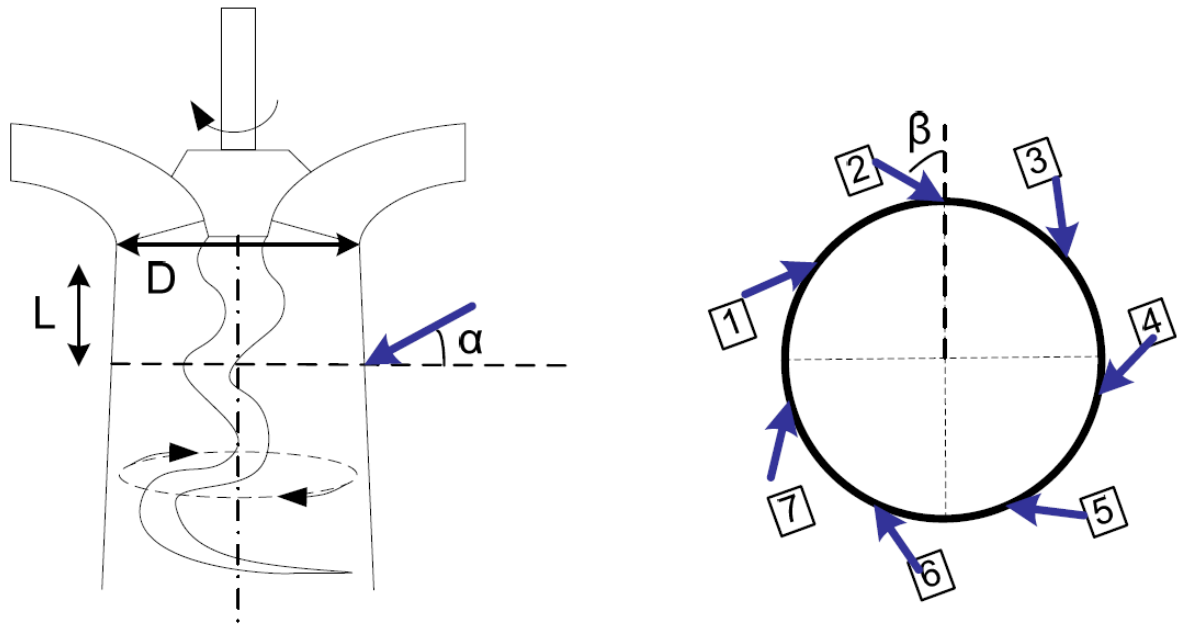

Figure 5-11 - Vertical and horizontal angles spatial representation [14]

Water is usually taken from the penstock where pressure already exists, but can also be pumped when water head is low or when other water sources are used. Such alternative water sources could be from the spiral casing or further down in the draft tube. [**7**]

The water jet provides angular momentum to the fluid in relation to the mass flow, velocity and the radius from the center of momentum in the manner depicted in the below expression and in Figure 5-10.

$$\tau_{nozzle} = \dot{m} * v * R = \pi * r_{nozzle}^2 * \rho_{water} * v^2 * R \ [Nm]$$

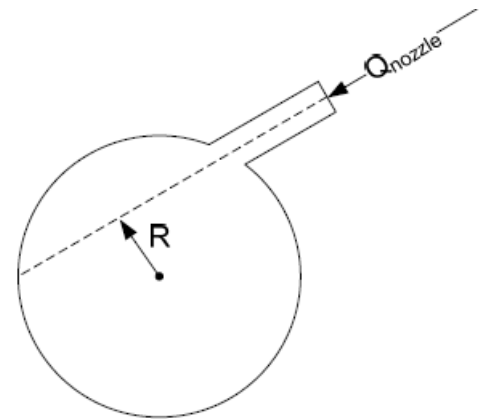**Figure 5-10 – Radius of swirling torque** [14]

Due to the large inertia of moving water in comparison to air, it is possible to change the flow characteristics dramatically by only using small volumes of fluid. This technique aims to counteract the swirl by introducing a counteracting swirl momentum. It can also, delay or avoid boundary layer separation by energizing the boundary layer. [**14**], [**15**]

H. Francke [14] states that there are many degrees of freedom related to the nozzle system such as vertical and horizontal alignment of nozzles as well as variation in flow rates and geometry. Also different number of nozzles could be used at different distances from the runner. All variables are depending on the operating conditions and the turbine. The expected results from the water injection system are presented below:

- Reduction in swirl strength
- Reduction in vibrations and pressure pulsations
- Help filling the center of the draft tube and smoothen the velocity profile (boundary layer)
- Better utilization of the draft tube, thus better draft tube efficiency
- Increase in the Francis turbine operating range

In general, a water injection system normally consists of the following parts seen in Table 5-3

Water Intake	Water can be taken from lower parts of the draft tube, the penstock, the spiral casing or from other accessible water source
Pumps	Used to give sufficient flow rates to the injection system. Taking water from a penstock with sufficient water head can avoid the need for a pump.
Water flow measurements	Various techniques used to measure the discharged water flow. Such techniques are mechanical, pressure-based, optical, acoustic, thermal or induction based.
Water piping	Pipes that conducts the water from intake to exit
Valves	Manual, safety and automatic valves. Automatic and safety valves can be remotely or automatically controlled with software or mechanical feedback
Vibration dampers	Dampers in series with the piping in order to reduce vibrations propagation
Feedback transducers	Usually vibration and pressure transducers but also other transducers such as spatial measurements may be used as feedback
Control system	Computer system monitoring operating conditions with feedback from transducers and regulates the nozzle flow in accordance to stored calibration data
Exit nozzles	Nozzles designed to give proper water jet without harmful noise

Table 5-3 – Typical water injection system components

In Figure 5-12 to Figure 5-17 on following pages are pictures of the water injection system installed at Skibotn power plant presented. The direction of water flow is indicated with a blue arrowed line. Pressure transducers have been mounted on valves as visible, something that really simplifies their installation procedure.

In Figure 5-12 is the control system overview tab visible, also providing with a schematic model of the system. Noteworthy is that a lockable manual valve is omitted from this overview that is visible in Figure 5-13 on the following page.
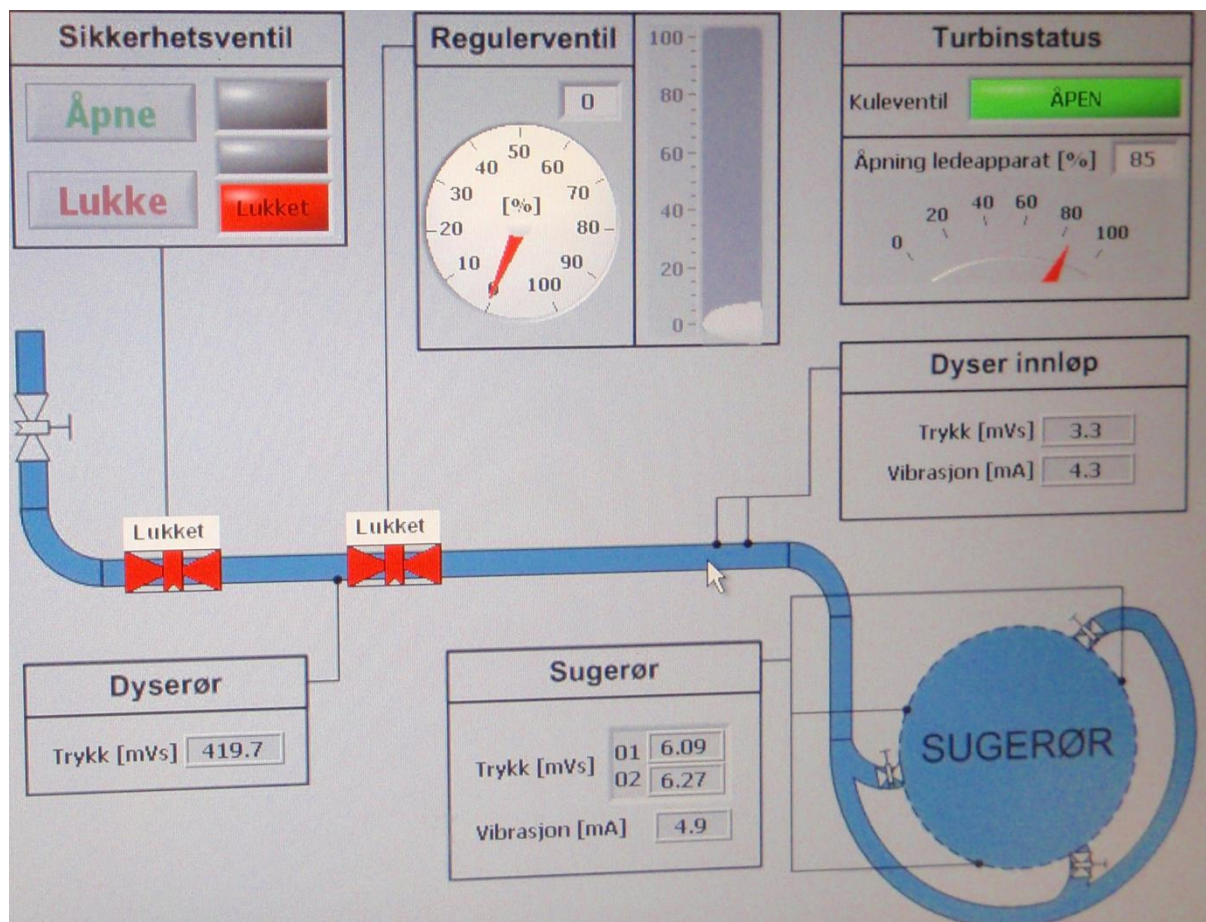

Figure 5-12 – Water injection control system overview

The nozzle flow set points used in the software is found from field tests at each operating point using feedback from the mounted transducers and stored in a database. Operating condition is measured with a system sample rate of 1000Hz and incorporates data from the last minute when changing output commands, which happens 4 times per second.

Figure 5-13shows the beginning of the water injection system with its connection to the penstock shown. Two manual valves where one is lockable, a water hydraulic safety valve and one automated regulating valve are coupled in series before entering the nozzle system inlet.

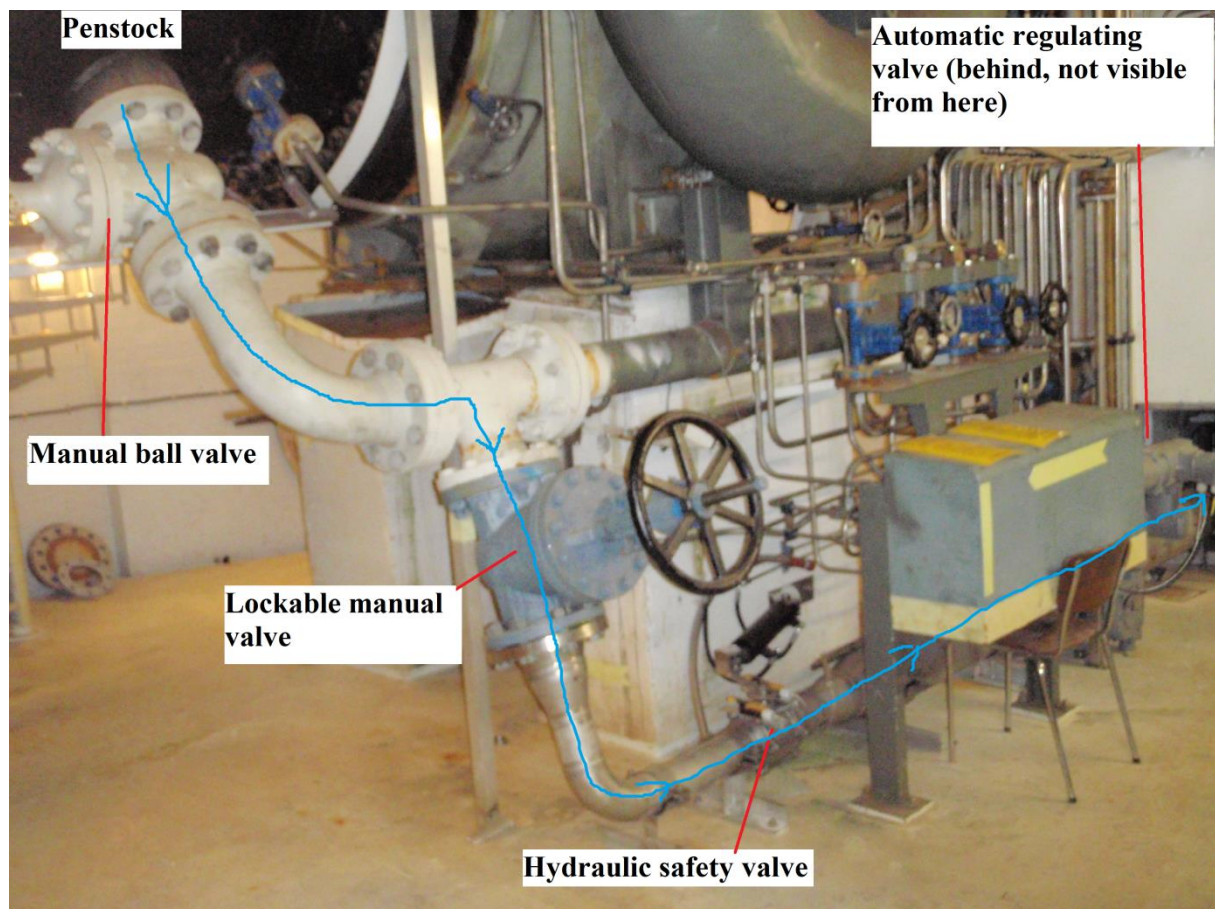**Figure 5-13 – Skibotn penstock installation**

Figure 5-14 shows the automated regulating valve and the nozzle pipe pressure transducer. This part was hidden in Figure 5-13 and regulates the water flow from the penstock to the nozzle system inlet. The valve is of the brand AUMA and is equipped with a motor and can be regulated by the control system.
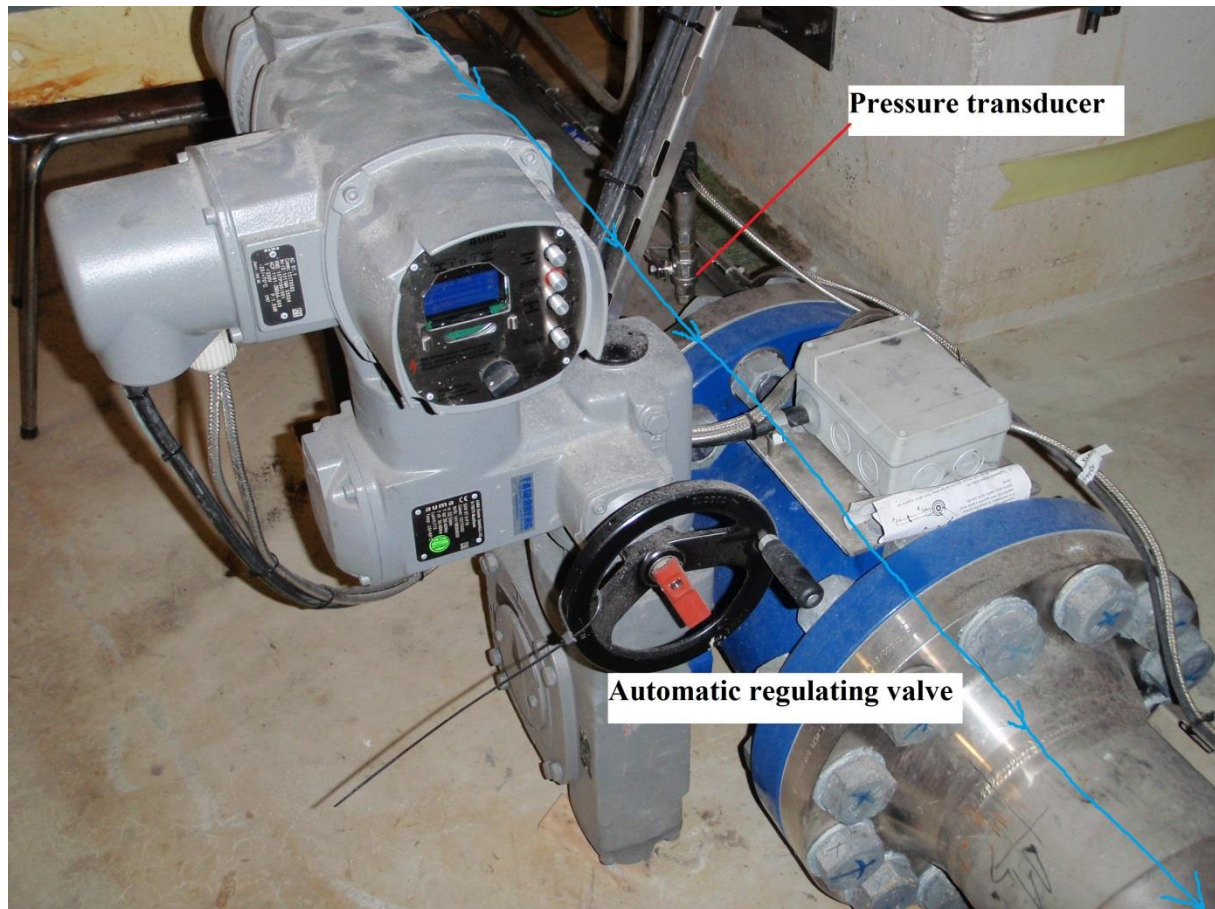

Figure 5-14 – Skibotn automatic regulating valve

After the water has passed the automated regulating valve it enters the so called nozzle system inlet seen in Figure 5-15. Here a pressure and a vibration transducer is mounted. Downstream from this part are the nozzles.
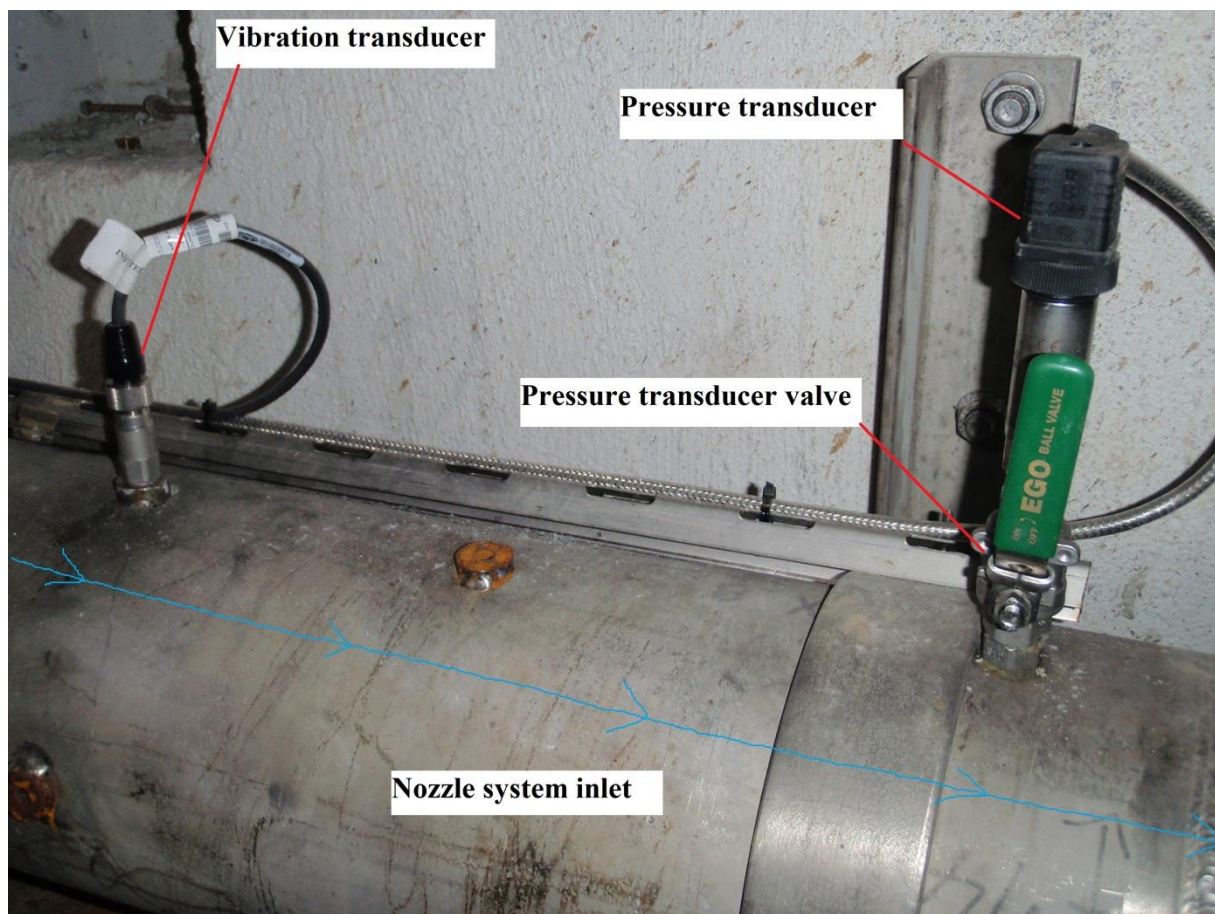
Figure 5-15 – Skibotn nozzle system inlet

Figure 5-16 shows the most upstream nozzle in the system with its manual valve and vibration damper. Water that is continuing at the left in the picture is connected to the two downstream nozzles.

Nozzles are mounted approximately 250mm downstream the runner, L/D=0.19 in Figure 5-11. The flow can be varied between 0-220l/s, which is approximately 1.2% of the nominal flow of $18\frac{m^3}{s}$.
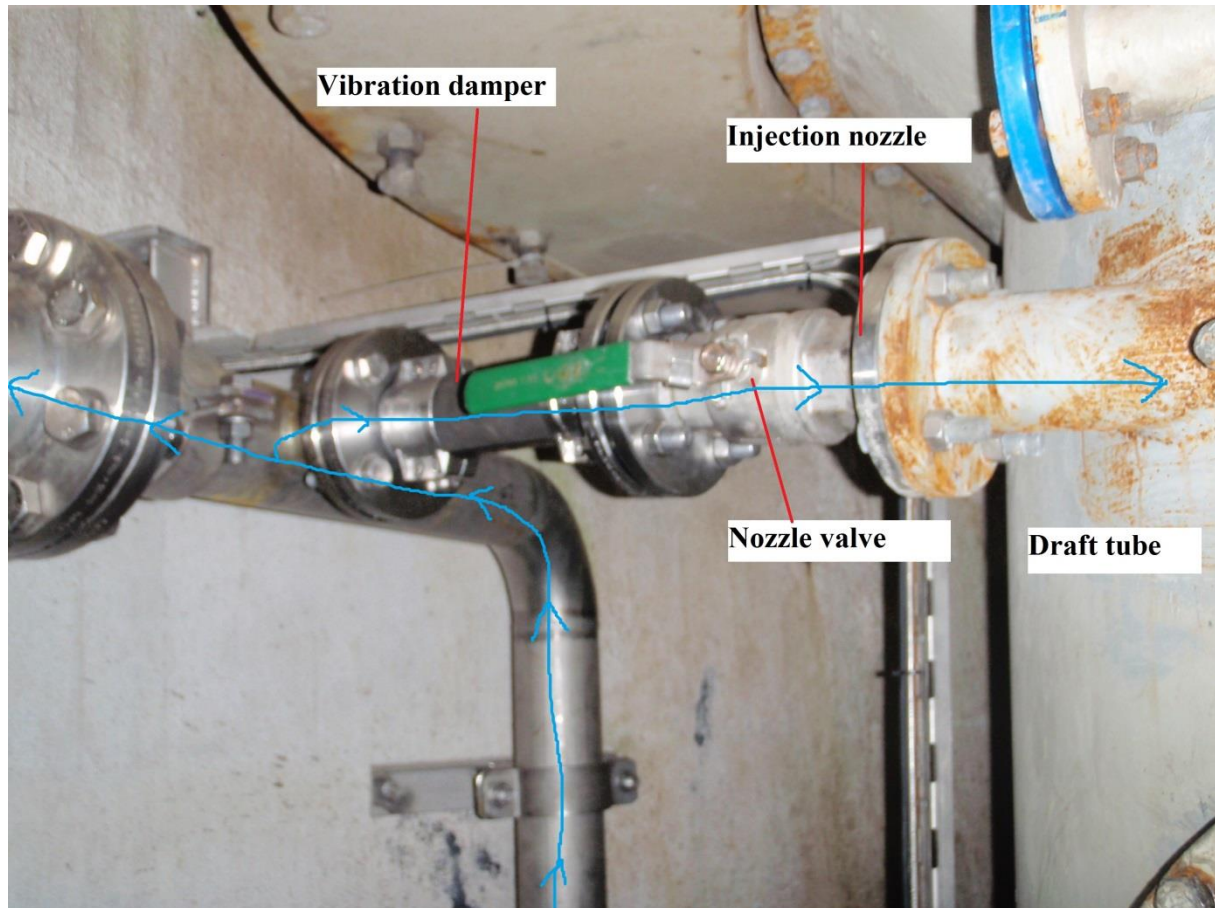
Figure 5-16 – Skibotn first nozzle inlet

Figure 5-17 shows the draft tube with the two first nozzle connections visible. The water continues on the right side behind the draft tube to the third nozzle. Residual transducer valves and nozzle connections from field tests are visible. To the left can be seen the vibration transducer and its intended position, this was not mounted at the time of visit.
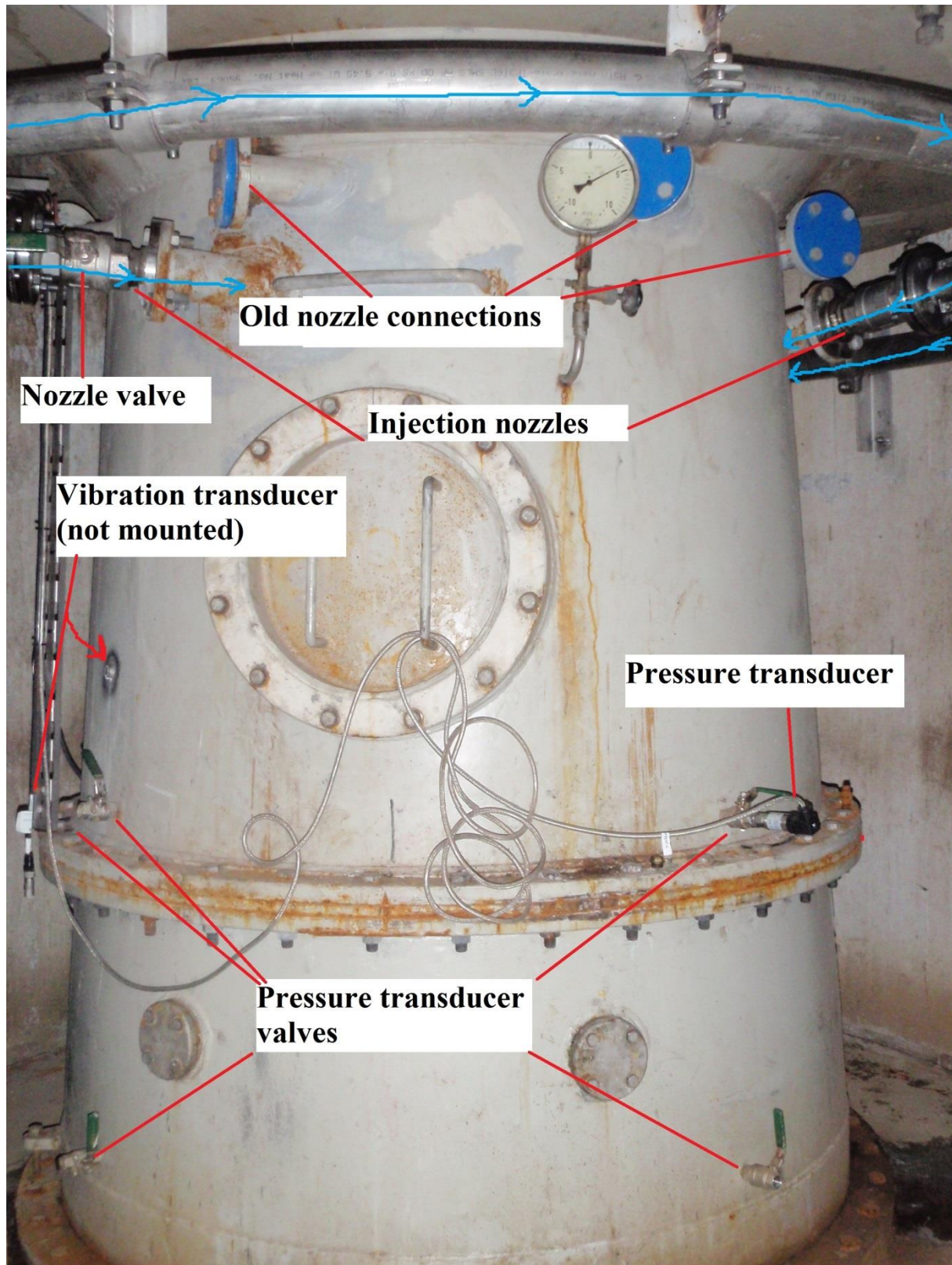
Figure 5-17 – Skibotn draft tube

5.4.3 Other countermeasures

An overview of some flow phenomena and the topics of their countermeasures are seen in Table 5-4

Boundary layers	**Vortex flows**	**Jets, wakes, mixing layers**
Separation Control	Forebody Vortex Control	Mixing Enhancement
Drag Reduction	Blade-Vortex Interaction	Jet Vectoring
Noise Suppression	Vortex Dynamics	Noise Suppression
Surface Shaping	Vortex Generation/Alleviation	Wake Modification

Table 5-4 – Flow phenomena and countermeasure

There has been many actions made during the years to mitigate the draft tube pressure surges and some of these countermeasures has been summed up together with their related benefits and losses and is presented in Table 5-5 on the following pages [**13**], [**14**], [**16**]

This table has no significance to the report aim but is presented to give further insight into some tested solutions.

Action	Benefit	Loss
Operational tools		
Avoid operation in exposed ranges	-Solving vibration and efficiency problems	-Reduction of availability -Loss of energy production -Harder to automate
Design		
Runner design with specified velocity distribution at exit	-Swirl and surge characteristics can be affected in certain ranges	-Affecting performance and cavitation characteristics
Draft tube design (angle, contour and length)	-Limited reduction of surge -Length affects the natural frequencies	-Loss of efficiency -Risk for boundary layer separation
Morphing turbine crown	-Increased operational range	-Expensive and technically advanced installation
Asynchronous guide vanes	-Improves transient response -Reduces risk of hydro acoustic resonance	-Structural problems
Geometrical inserts		
Fins attached to draft tube wall	-Reduces surge at part loads -Increases surge frequency -Works for all machine sizes	-Fins are sometimes subjected to cavitation erosion and structural vibrations -Loss of efficiency especially at high loads
Stiff cylinder mounted with tripod	-Good experience with pumped storage and mixed turbines -Effective surge reduction -Tripod can be used as vent pipe, but is normally not needed	-Loss of efficiency, increasing with specific speed and load -Tripod is subject to cavitation -Lateral forces acts upon cylinder -Not practicable for large units
Coaxial hollow cylinder, curving with the draft tube elbow	-Damping pressure surges -No significant efficiency loss -Increase of surge frequency -Tripod may be used for air injection	-Heavy structural problems -Limited to medium sized units
Combination of hollow cylinder and prolonged fins	-Damping pressure surge	-Heavy structural problems -Loss of efficiency -Limited to medium size units -Subject to cavitation
Extension of the runner cone	-No significant efficiency loss -Length can be varied with operating point	-Increased lateral forces upon bearings -Only small effects on vibrational behavior
Long runner cone extension attached with double tripods	-Damping pressure surges -Tripods may be used for air injection	-Structural problems- -Loss of efficiency
Cone extension "snorkel" with tripod	-Sometimes good surge damping effects -Tripod may be used for air injection	-Less effective then other means without air injection
Pipe spanning the draft tube	-Relatively cheap solution -Only small effect on efficiency	-Not effective without air injection

		-Only for air injection -Only for medium sized units
Pure tripod	-No loss of efficiency -Tripod may be used for air injection	-Less effective than other means without air injection
Morphing skins	-Reduces pressure surges	-Structural difficulty -Possible loss in efficiency
Morphing cushions (adapts draft tube geometry to the flow by inflation)	-Reduces pressure surges -Can be regulated to operating point -Regulates flow frequencies	-Structural difficulty -Needs compressor
Fluid injection		
Air injection of small air volumes	-Reduces high frequency noise -No loss of efficiency -Reduction of cavitation erosion when injected upstream of the runner blades -Damping shock wave from cavitating vortex rope	-Normally no reduction of low frequency amplitudes -May cause resonance problems
Air injection of large air volumes	-Significant surge reduction -Damping power swing	-Primary loss of efficiency -Secondary loss off efficiency due to compressor input power -Uneconomic
Air injection via atmospheric venting through runner cone	-Sufficient air volume available -Reduction of surge with high flow rates relative to air	-Not working in pumped storage schemes with high submergence -Venting pressure varies with unit output and vortex precession
Water injection axially through the runner cone	-Reduces pressure surge -Increase production -Easy to automate -Can be shut off when desired -Can be calibrated to each operating point -Hydraulic efficiency may increase in some operational modes -Pressure difference in the draft tube wall and injection area can be used for flow feedback [17]	-Loss of efficiency due to water passage -May require a pump for optimal effect -Structural problems in the shaft
Water injection by nozzles mounted below the runner at an angle to the draft tube wall, using water from the pressure shaft	-Reduces pressure surges -Increases production -Easy to automate -Can be shut off when desired -Can be calibrated for each operating point -Hydraulic efficiency may increase for some loads	-Loss of efficiency due to water passage -Consist of many parts -May require a pump at low water heads
Rotating valve exciter (A rotating ring with slips in the draft tube, passing water valves at desired speeds)	-Specific frequencies can be attenuated -Low power consumption -Low water consumption	-Structural difficulty

Table 5-5 – Some countermeasures to the draft tube pressure surge

5.5 Case study Lövhöjden power plant

The case study is made at Lövhöjden and Ålviken power plants see Table 5-6. The machine installed at these power plants is of Francis type and come in two sets with different water heads. These machines are producing at highest efficiency and best price and are usually operated simultaneously, equating to an amount of 14,5MW marketable production. They are often turned off at low price periods to save water and do not require to pass any certain flow at these times.

	Lövhöjden (large reservoir)	Ålviken (small reservoir)
Location	Stor-forskvattnet (Upstream)	Lill-foskvattnet (Downstream)
Rotation speed	600rpm	600rpm
Rated capacity	8,5MW	6,0MW
Annual production	24GWh	17GWh
Water head	99m	75m
Maximum flow rate	$10m^3/s$	$10m^3/s$
Reservoir head variation	11m	40cm

Table 5-6 – General information of Lövhöjden and Ålviken power plants

Both of these machines are horizontally mounted and do not have hollow shafts, making central air admission more difficult. In Figure 5-18 is a schematic overview of the turbine.
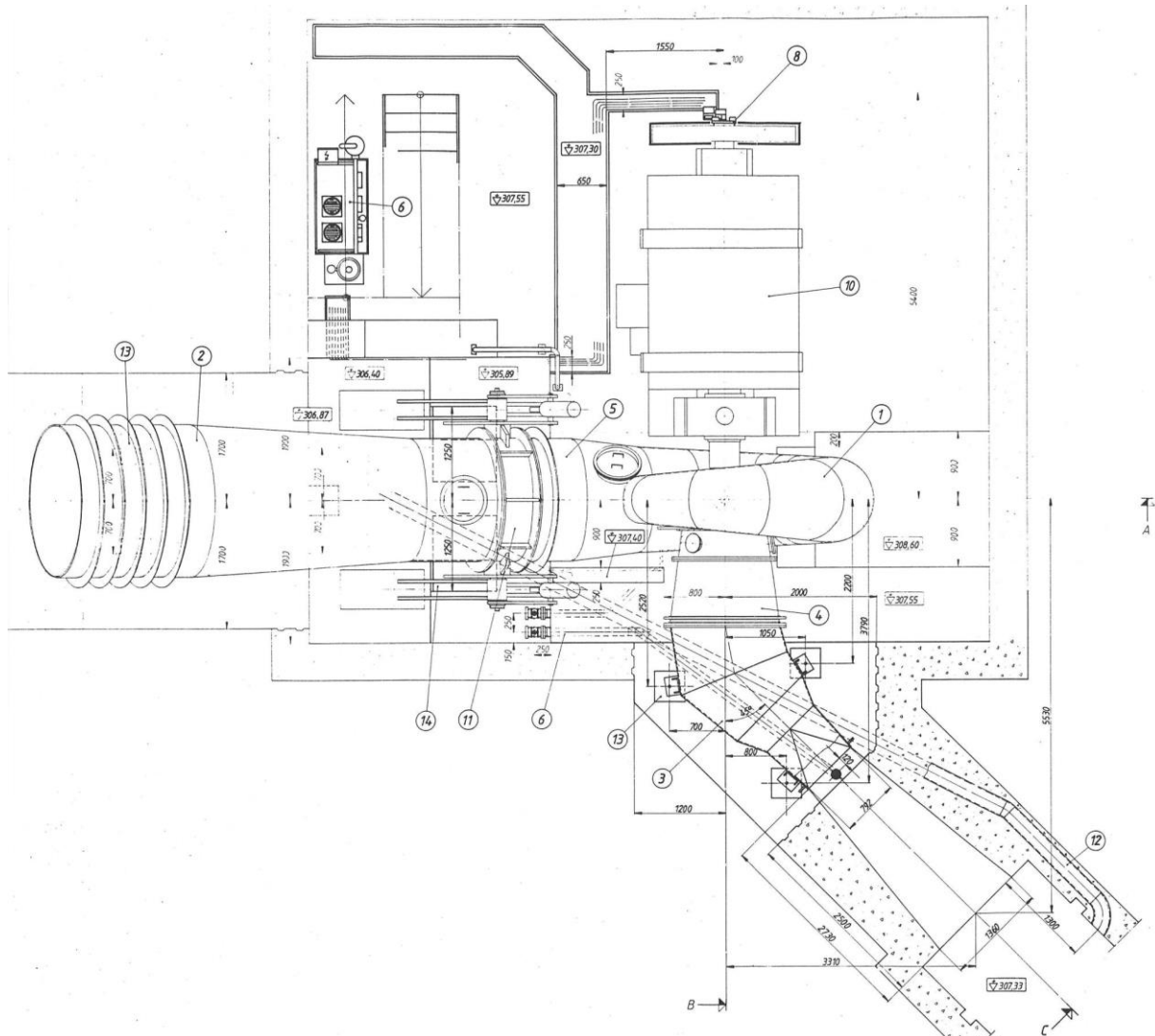

Figure 5-18 – Ålviken turbine, schematic overview, seen from above [18]

Lövhöjden suffers from an undesired operating point at 5,5MW load and has an compressed air injection system installed to ease the many start and stop procedures. Increased part load availability from fluid injection techniques are of moderate interest at these facilities since no minimal flow is required to be passed according to water rights-judgments. They would experience tradeoff in efficiency and loss of possible revenue due to usage of the water storage at low price periods. The possible benefits from fluid injection is increase in reliability and overload capabilities, this is however restricted by the installed generator size.

Lövhöjden has the first and larger reservoir called Stor-forskvattnet, in which the water surface is allowed variations between 476-487MAMSL[8], which equates to 11m allowed head variation.

Ålviken has the second reservoir called Lill-foskvattnet in which the allowed water surface variation is between 387,80-388,20MAMSL, which equates to 40cm variation.

At maximum flow of $10\frac{m^3}{s}$ it takes 4hours and 28minutes to reach the water head surface limits at Lill-foskvattnet according to Jämtkraft software simulation. Suggesting that either both system need to be equipped with injection systems or Lövhöjden is equipped and their production schemes needs to be altered.

Then full load production time at Ålviken needs to exceed the one of Lövhöjden with a time that is proportional to the discharge and time that Lövhöjden has operated at since the last stop of Ålviken and it is not allowed to exceed this time by more than the time needed to reach the lower surface limit. Restraints on the Ålviken run time is illustrated in the below expression.

$$T_{100\% \text{ Löv}} + T_{X\% \text{ Löv}} * Q_{X\% \text{ Löv}} \leq \boldsymbol{T_{100\% \text{ Ål}}} \leq T_{100\% \text{ Löv}} + T_{X\% \text{ Löv}} * Q_{X\% \text{ Löv}} + T_{Lim}$$

$T_{100\% \text{ Ål}}$ is the time of full discharge at Ålviken

$T_{100\% \text{ Löv}}$ is the time of full discharge at Lövhöjden

$T_{X\% \text{ Löv}}$ is the time of some load differentiating from nominal load at Lövhöjden since Ålviken stopped

$Q_{X\% \text{ Löv}}$ is the load factor at Lövviken and is the quota between discharged flow and nominal flow

T_{Lim} represents the time needed to reach the lower limit of the allowed water surface due to full discharge at Ålviken and is held less or equal to 4h28min. It should be noted that this term depends on the current water level and difference in flow at Ålviken and Lövhöjden.

Frequencies that are expected in the case study can be calculated with information that the turbine is equipped with 20 guide vanes and 16 runner blades. The expected frequencies to be found at Lövhöjden and Ålviken turbines are presented in Table 5-7 below

Runner frequency	$f_n = 600/60 = 10Hz$
Runner blade frequency	$f_b = 10 * 16 = 160Hz$
Guide vane frequency	$f_g = 10 * 20 = 200Hz$
Rheingans frequency	$(10/4 \leq f_r \leq 10/2)\ 2,5Hz \leq f_r \leq 5Hz$

Table 5-7 – Expected pressure pulse frequencies in the flow at Lövhöjden and Ålviken

The dominating pressure pulse amplitudes are assumed to be in the range of 2.5-5Hz.

---

[8] Meters Above Mean Sea Level

6 Results

In this sector results from each technique are gathered. Good potential for reduction of deleterious effects in the draft tube has been found for both techniques. This part has been subdivided into technical and economic summaries.

6.1 Technical summary

Included in the technical summary are reported technical effects of the fluid injection techniques.

At the case study no proper aeration path was found due to the unhallowed shafts. Peripheral aeration could be an easier alternative but no estimates were attained for this technique. A conclusion is that technical implementation of peripheral water injection is to be preferred at the investigated turbines.

6.1.1 Air injection

The design of the aeration system in a Francis turbine has a significant impact on the efficiency, performance and reliability. Turbines may experience small to moderate efficiency losses of about 0.2%-1%, even with the aeration system shut off if geometrical modifications such as baffles and thicker blade design are present due to the aeration system. With aeration active, turbines can experience a significant loss of efficiency in the range of 3%-10% depending on the location and amount of injected air. Turbines that are using the existing vacuum breakers as an aeration path and those who have central baffles installed can experience significant reduction in capacity and flexibility [10]

Air injection is often used in order to increase the DO[9] levels in the water to reduce the risk of damaging the aquatic habitat downstream the power plant. It has been found that distributed aeration through the trailing edges of the runner blades has the smallest effect on efficiency as well has the highest increase in DO, followed by peripheral aeration. [10]

Little is published on effects of aeration on turbine efficiency but it is generally decreasing in relation to the air flow rate relative to turbine discharge. Information about losses in efficiency has sometimes been collected in relation to test aiming to increase the DO levels. In turbines with high submergence such as pumped hydro turbines, the effect of air injection can become counterproductive in certain cases due to resonance in the draft tube pulsations induced by the of the injected air. [5]

Air admitted centrally through the runner cone can reduce the oscillation amplitude of the vortex rope, hence reducing the risk of hitting the draft tube walls. [19] It is also a zone where atmospheric air easily can be admitted with good results. The air-water mixture will affect the systems hydraulic response and the excitation of natural frequencies in the water passage system.

R. Fraser et al found in model tests that an efficiency increase of almost 4% using centrally admitted air through the runner cone was achieved around 50% discharge, no tests were made at lower discharge then this and there was a 1-5% loss in efficiency at all operating modes above this [20]

When testing an aeration system through the whole operating span the central air will in general have the largest influence on turbine efficiency with an almost linear increase to air flow, but also provides with a good method of mitigating the vortex rope. At low air flows, peripheral aeration shows the lowest effects on turbine efficiency but at increasing air flows a distributed aeration systems seem to result in the lowest efficiency losses. [12]

---

[9] Dissolved Oxygen

It is stated by R. Fraser and N. Désy that it is more favorable for machine performances to use continuous air admission around the machine instead of having a unique injection point such as central aeration through the runner cone or distributed aeration with a few points around the draft tube. [20]

Andritz, Alstom, American Hydro and Voith Hydro are major turbine manufacturers that are operating on the market of designing aerating turbines. P. March has conducted experiments presented that show the effects on efficiency from central aeration of an eighty year old runner and two modern runner installed 2002, The efficiencies are normalized to four state of the art aerating runners installed 2008 using distributed aeration, seen in Figure 6-1. [12]
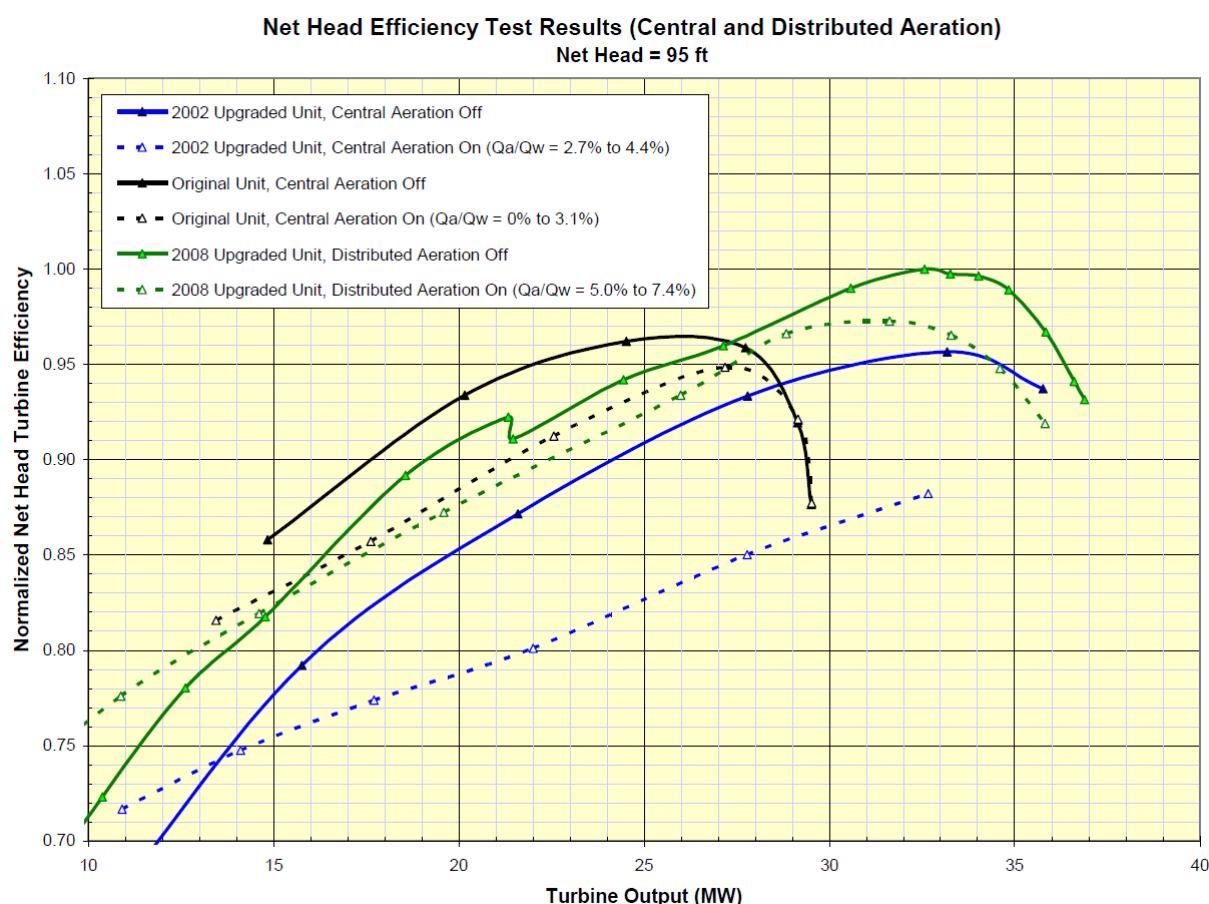

Figure 6-1 – Normalized hydraulic performance of central air injection [12]

Ulith found 1968 in tests carried out on a model turbine that the most effective location for compressed air injection is in the ring shaped space between the wicket gates and the runner inlet. Here airflow corresponding to only 0.08% of turbine discharge was required in order to achieve a satisfactory damping effect. Additionally injection at this location did not cause any noticeable reduction in efficiency. [6] Confirmed by [21]

At Itaipu power plant there has been many problems and machine stops due to the aeration system installed, averaging to 1.35 failures per year. Worst problems were due to valve failures and a third of the stops were due to accidental protection actuations. It was presented that when studying other machines the presence of the aeration system was responsible for 3.64% of machine stoppages during 1991-2012. Noted should be that the Itaipu aeration system is connected to the spiral casing above the cavitating zone of the runner. [22]

In Figure 6-2 is experimental results found by P. March showing the effect on efficiency with peripheral aeration system with respect to the upper load curve.
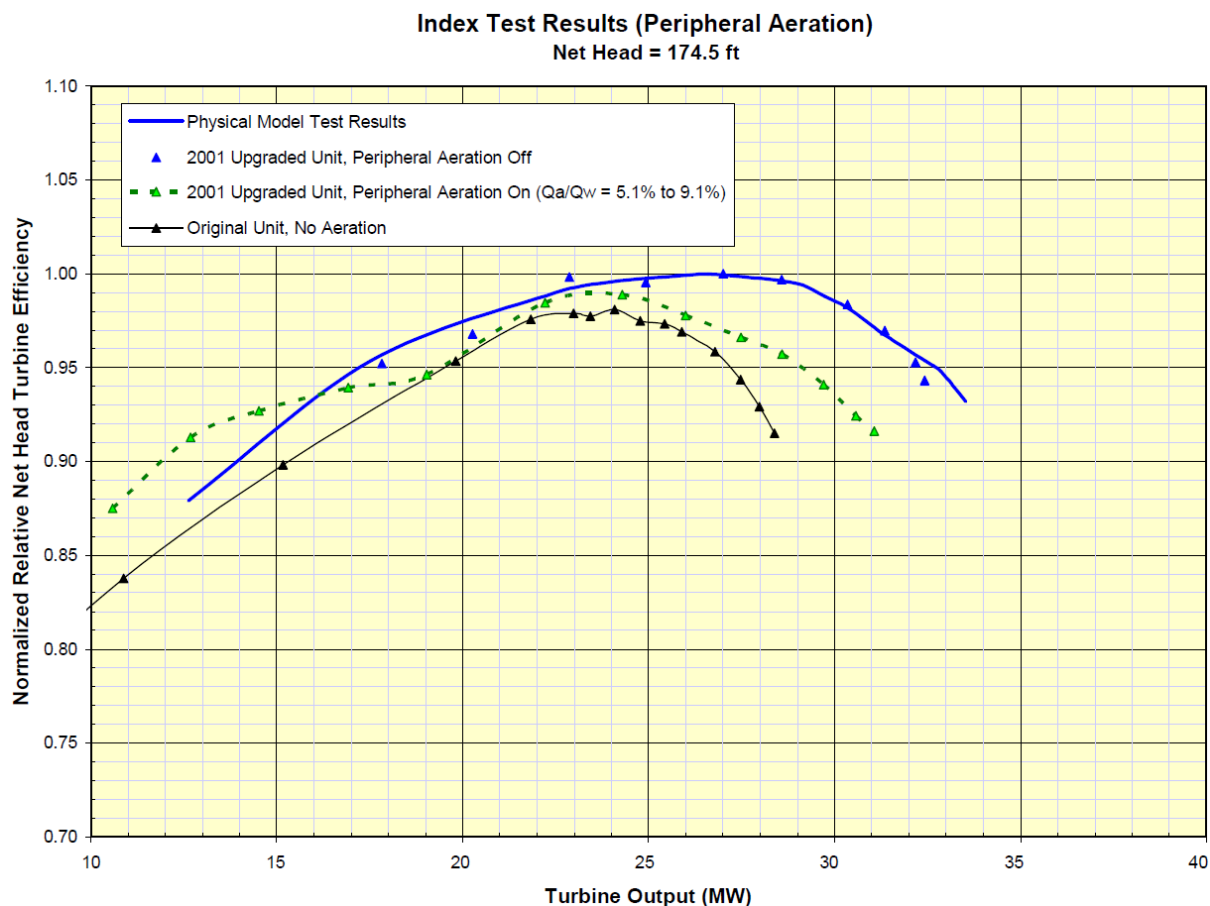
Index Test Results (Peripheral Aeration)
Net Head = 174.5 ft

Figure 6-2 – Normalized hydraulic performance of peripheral aeration [12]

At high tail water or at highly submerged turbines compressed air is needed. It is stated by H. Grein that 3% of the turbine discharge is required in order to achieve a significant pressure pulse reduction, which causes significant losses in efficiency due to the power expenditure of the compressor. [**16**]

Gibberd, J. J. found diagnosing a 30MW UK hydro station that the penstock vibrations around 30% of runner speed was successfully mitigated by air injection. Suggesting that mitigation of upstream flow problems can be successfully achieved with this technique. [**23**] Presented in [**5**]

S. Muntean et al found in a case study that for air injected through a tripod located below the runner exit the operation was significantly improved at 69.1% of BEP but was worsen at 41.8% of BEP. A mitigation of the pressure spectrum content was observed in this study and the conclusion made included that individual investigation of each turbine shall be made in order to identify the dangerous operating regimes when using air control [**24**]

In general P.Döfler et al mentions many times in [**5**] that centrally introduced air, both injected in small quantities and admitted from atmosphere connections has proven useful when eliminating parasitic pressure pulsations. It is also stated that straight conical draft tubes as well as horizontal axis turbines has a lower response to aeration since air can easily escape and is not well retained in the vortex.

~ 28 ~

6.1.2 Water injection

Mainly results found by H, Francke regarding Skarsfjord, Skibotn, Svorka and a test rig of Tokke power plant is presented and investigated in this section. Results are separated according to turbines utilizing the peripheral draft tube water injection technique.

6.1.2.1 General overview

Slightly different versions of the injection system has been developed and tested at these power plants, all yielding different but positive results, see Table 6-1 below for a short summary of these facilities.

	Skarsfjord	**Skibotn**	**Svorka**
Owner	Troms Kraft Produksjon	Troms Kraft Produksjon	Statkraft
Turbine	Francis	Francis	Francis
Manufacturer	Kværner	Kværner	J.M.Voith
Head	150m	430m	260m
Power rating	4,04 MW	72MW (55 MW BEP)	25MW
Annual Production	18 GWh	355 GWh	101 GWh
Rotational speed	750 rpm	600 rpm	600 rpm
Year	1994	1979 (runner 1995)	1961

Table 6-1 – Short summary of investigated facilities utilizing the water injection system [14]

The reasons for installing injection systems are varying for these facilities.

- Skarsfjord has acted as a test facility used in development of system design with a manually controlled injection system.
- Skibotn were required to pass water flows in accordance with water rights judgment that coincided with a dangerous operation regime of the turbine.
- Svorka experienced cavitation problems suspected to be related with draft tube pressure surges.

It was found that the water injection worked with some condition restraints and gave a reduction in pressure pulsations both in laboratory and field experiments. It also had a surprisingly positive effect on the overload conditions in a Tokke power plant model turbine, considering that the nozzle flow was aligned with the swirl direction. An increase in hydraulic efficiency was found both in laboratory and in field measurements, the overall efficiency was however always reduced due to water being bypassed [**14**]

Table 6-2 [**14**] below summarizes the effects of the Skarsfjord and Skibotn power plants after installation of the system.

Skarsfjord	Skibotn
• Rheingans pulsation were slightly Reduced • STD[10] of pressure measurements was reduced with use of nozzles • Static wall pressure increased with number of activated nozzles • Negative pressure in the draft tube • Jet noise occurred from the nozzles when activated	• Rheingans pulsation were strongly reduced • STD of pressure measurements increased with the use of nozzles • Static wall pressure decreased with number of activated nozzles • Overpressure in the draft tube • Jet noise occurred from the nozzles when activated

Table 6-2 Summary of results from Skarsfjord and Skibotn

Similar to the Skarsfjord and Skibotn power plants are the comprehension of more steady operation of the units when using the water injection system. At Skarsfjord this was due to reduction of random pressure noise and at Skibotn due to noticeably smaller vibration in the draft tube cone. [**14**]

In Table 6-3 below is a summary of the test injection systems info at Skarsfjord and Skibotn

	Skarsfjord	Skibotn
Number of nozzles	5	7
Nozzle outlet diameter	13 mm	27 mm
Nozzle angle α	8 deg	0 deg
Nozzle angle β	35 deg	35 deg
Nozzle flow rate	0-32 l/s	0-220 l/s

Table 6-3 – Nozzle info at Skarsfjord and Skibotn

Nozzle angles α and β are fixed and are illustrated in relation to the turbine in Figure 5-11

The vertical angle α showed strong relation to pressure pulsation reduction and the optimal angle was dependent on the turbine operating condition. This angle also had a noticeable effect on the draft tube hydraulic efficiency with losses due to nozzle flow disregarded; this was especially found at part load conditions. In general it was found that nozzles aimed downstream improved the hydraulic efficiency and nozzles aimed upstream could reduce the hydraulic efficiency. The best swirl reduction was also found when nozzles were aimed downstream [**14**]

The horizontal angle β showed some relation to the reduction of pressure pulsations and best results were found at the lowest tested angles. It did not affect the hydraulic efficiency notably but influenced the swirl reduction at positive values of α [**14**]

Common results of Skibotn and the Tokke test rig is that the correct nozzle flow is needed for the desired effect. Too high flow induced "jet noise" from the nozzles and too low flow did not dampen the pressure fluctuations satisfactory. At the optimal point the pressure pulsations were damped without the noise becoming a problem. [**14**]

---

[10] Standard Deviation

6.1.2.2 Skarsfjord

See Table 6-4 for a short summary of the Skarsfjord power plant.

Owner	Troms Kraft Produksjon
Location	Ringvassøy, Tromsø municipality, Troms county
Installed capacity	4MW
Water head	150m
Turbine	Francis
Turbine power	4,04MW
Rotational speed	750rpm
Annual production	18GWh

Table 6-4 – Skarsfjord power plant

Irregular pressure slams were present when operating the Skarsfjord power plant at 50% load. The sounds from these were audible throughout the plant and outside the draft tube outlet. After activating one or more nozzles, these pressure slams disappeared immediately. [14] This facility is also affected by large water head variations due to tidal variations; this creates a dynamic operating environment for the runner.

Measurements performed involved pressure pulsations in draft tube, pitot static measurements in draft tube cone, nozzle flow and hydraulic efficiency. Nozzles were mounted approximately 340mm downstream the runner outlet, L/D=0.52 in Figure 5-11.

The measurements led to an increase in static pressure at the draft tube wall with increased number of activated nozzles with the exceptions of when going from zero to one nozzle and the fact that lower static pressure was found using five nozzles then four at some operating points. [14]

The hazardous operating point was approximately in the area of 35%-50% load and appeared to become reduced with nozzle activation, irrespective to the number of nozzles activated, see Figure 6-3.
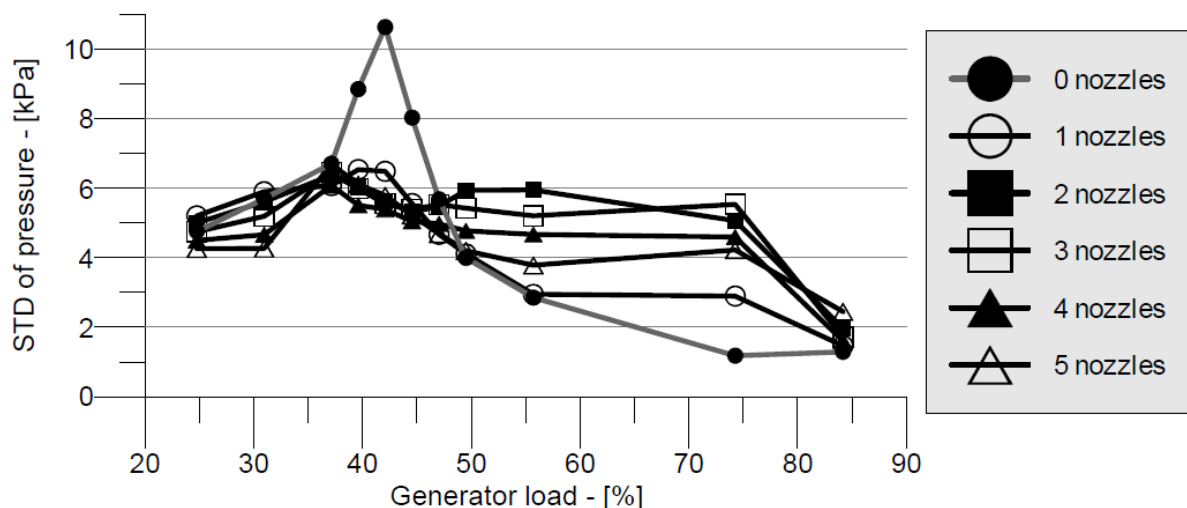

Figure 6-3 – STD of draft tube pressure as function of generator loads with different number of activated nozzles [14]

The pressure seems to decrease at the lowest load region with the number of activated nozzles and at the high load region the opposite appears to happen. The fluctuations corresponding to a rotating vortex rope was found to be reduced most effectively using 2 or 3 nozzles but was still present, suggesting that the vortex still rotates inside the draft tube. [14]

It was found that the hydraulic efficiency increased linearly with nozzle flow up to a 0.6% increase as depicted in Figure 6-4 below. Dahlhaug and Brandåstrø found that the total efficiency of the system was reduced with 2.4%-4.6% with nozzles activated. [**25**] found in [**14**]
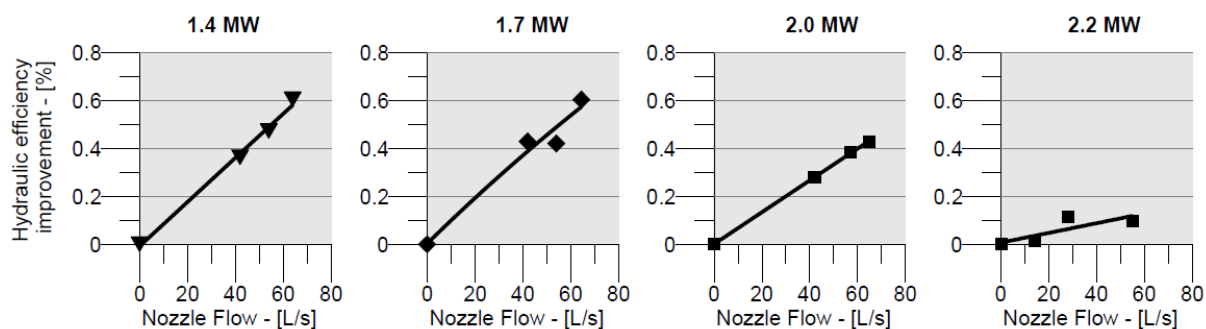

Figure 6-4 – Measurement of hydraulic efficiency improvement with nozzle flow at Skarsfjord October 2005 [14]

On the following page in Figure 6-11 is the results of pressure readings when operating at 43% load using different number of activated nozzles.

6.1.2.3 Skibotn

See Table 6-5 for a short summary of the Skibotn power plant.

Owner	Troms Kraft Produksjon
Location	Skibotn, Storfjord municipality, Troms county
Installed capacity	80MW
Water head	430m
Turbine	Francis
Turbine power	72MW (BEP at 55MW)
Rotational speed	600rpm
Annual production	355GWh

Table 6-5 – Skibotn power plant

At the location of this facility the water-rights judgment requires that around $4\frac{m^3}{s}$ of water is continuously flowing between June and October. Before installation of the water injection system this operating point was hazardous and this water flow was not passed through the turbine for power production. This flow amounts to about 15MW electricity production at the present water heads.

At this facility the measurements performed by Francke aimed to measure draft tube pressure pulsations, vibration of the nozzle system, run-out of the shaft and nozzle inlet pressure and flow.

The averaged pressure was found to be the lowest with 3 nozzles activated but already with 1 nozzle active a significant reduction of the pressure pulsations were achieved, see Figure 6-5 below.
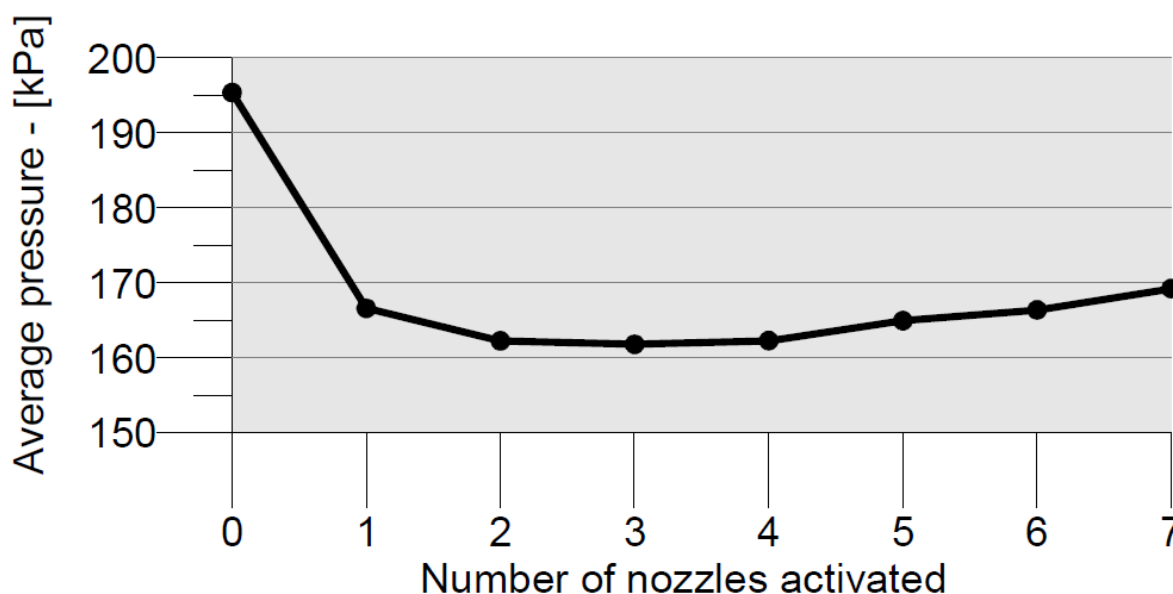

Figure 6-5 – Average draft tube pressure at 24MW with different number of activated nozzles [14]

In this facility additional information from measurements of shaft run-out fluctuations is available from the already existing control system. Below, in Figure 6-6, readings are shown with the number of activated nozzles present in between the peaks. [**14**]
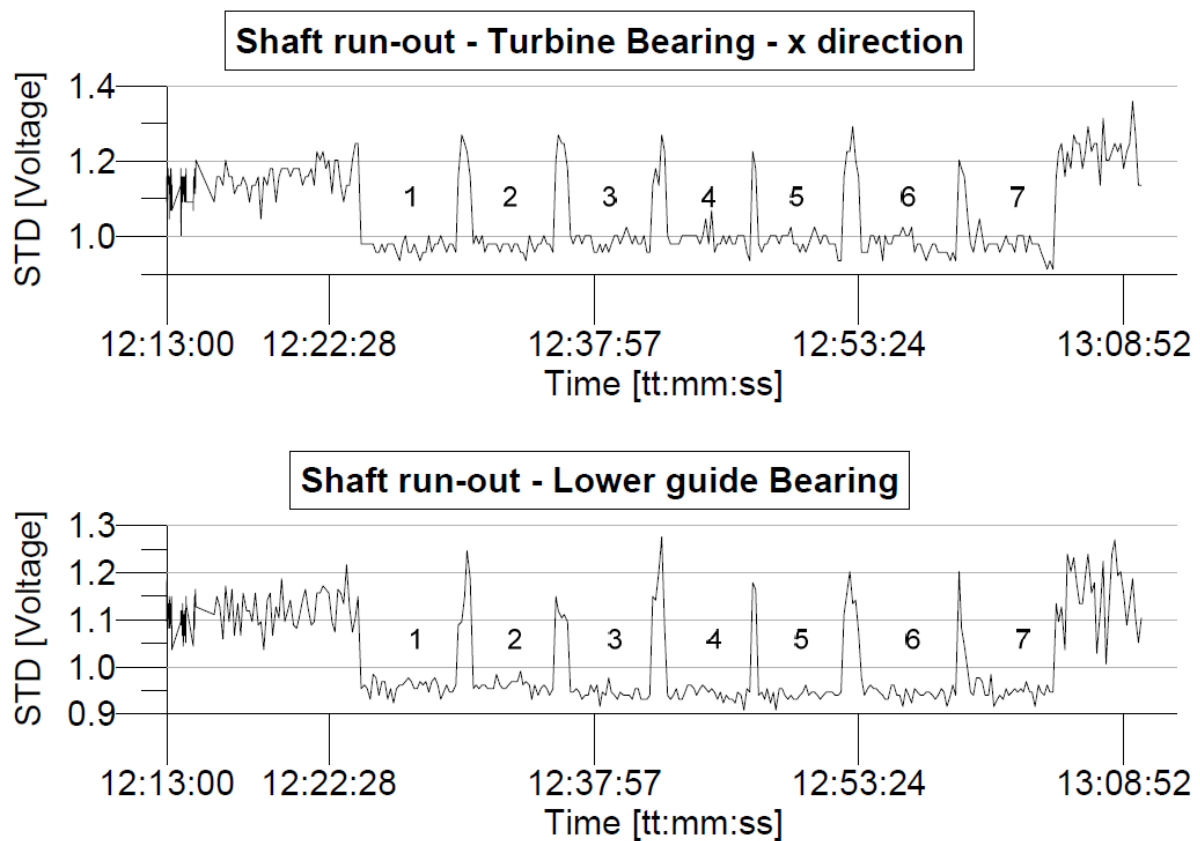
Figure 6-6 – Shaft run out measurements with different number of nozzles activated [14]

This suggest that axial forces are reduced using the nozzle system hence a positive effect on the turbine and generator bearings life times can be expected.

On the following page in Figure 6-7 is pressure measurements at 50% load presented using different number of activated nozzles. To the right is a FFT[11] up to 10Hz for each scenario.
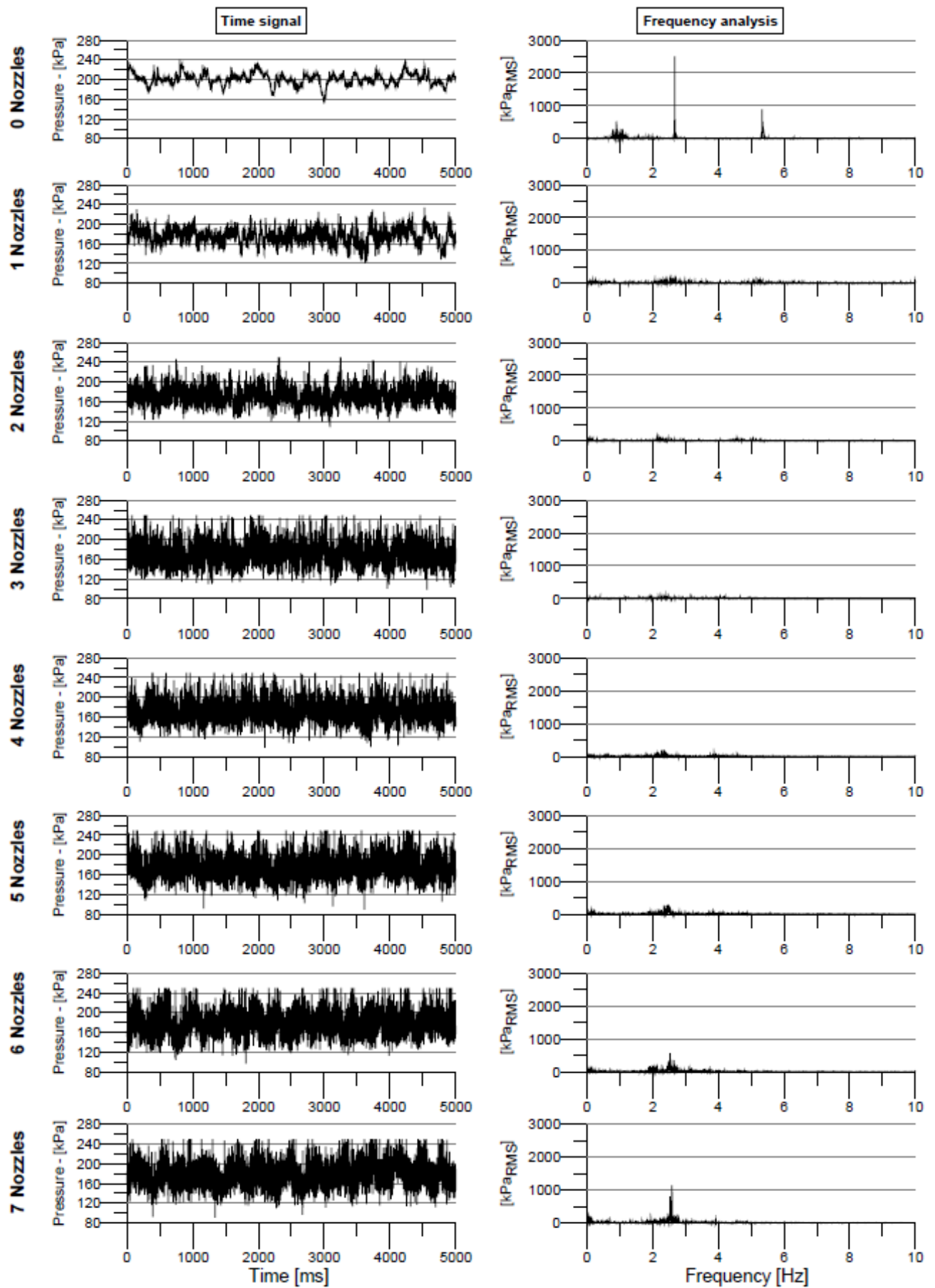
---

[11] Fast Fourier Transform

Figure 6-7 – Skibotn draft tube pressure and FFT, at 24MW with different number of activated nozzles [14]

6.1.2.4 Tokke model turbine

H. Francke has conducted measurements at a model of the Tokke power plant, see Table 6-6.

Owner	Statkraft
Location	Tokke municipality, Telemark
Installed capacity	480MW
Water head	377m
Turbine	4xFrancis
Turbine power	4x110MW
Rotational speed	375rpm
Annual production	2203GWh

Table 6-6 – Tokke power plant

Francke observed from the measurements that a considerable vibration occurred at high swirl numbers, which was radically reduced as nozzles were activated. The model was able to operate without difficulties at part load, but a moderate increase in surge was found at two part load and one over load condition and tests were performed at these loads.

It was also found that the cavitating vortex core due to overload is not influenced significantly by the use of nozzles, however the reduction of pressure pulsations are prominent and can be seen as a step function of nozzle flow. This is depicted in Figure 6-8 with the set value of 3litres/s nozzle flow. [14]
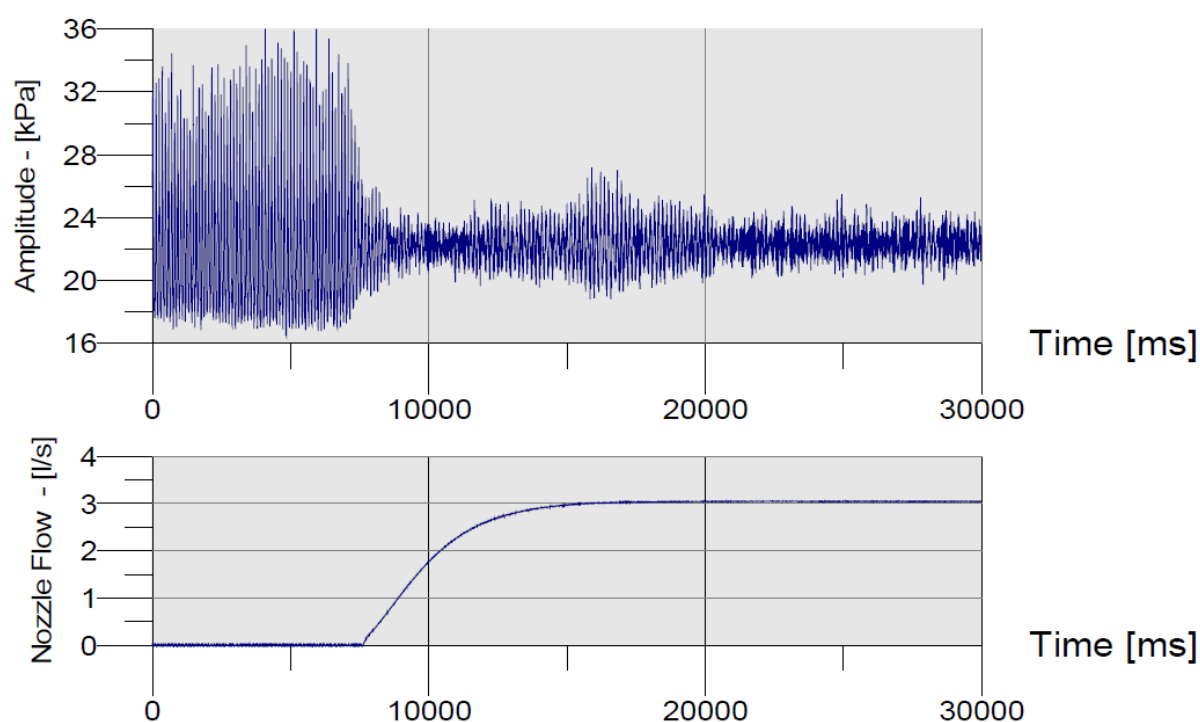

Figure 6-8 – Tokke model turbine pressure pulsation at overload when nozzles are turned on [14]

A trend with considerable correlation can be observed in the overload point where the axial loads seems to be reduced as nozzle flow increases. The standard deviation of axial shaft load in relation to nozzle flow is seen in Figure 6-9 below. [14]
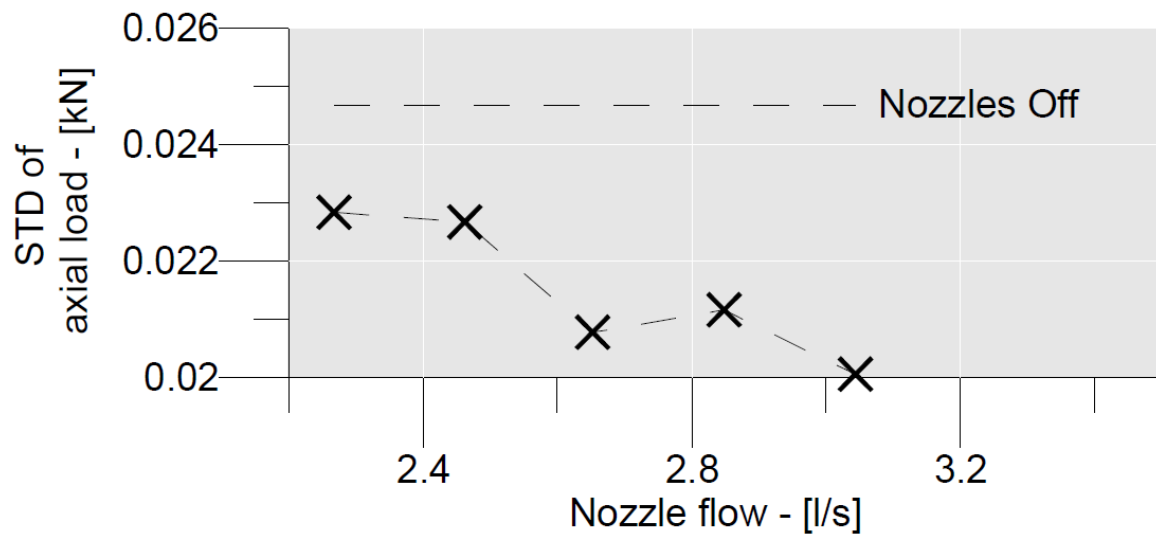
Figure 6-9 – Tokke model turbine axial load fluctuations measured at overload as a function of nozzle flow [14]

The nonlinear trend further suggests that nozzle flow should be carefully matched to each load condition in order to avoid unnecessary nozzle flow and jet noise.

It was also found that the Tokke model turbine pressure spikes at part and full load appears to be different in both size and in appearance of the pressure spikes as seen in Figure 6-10
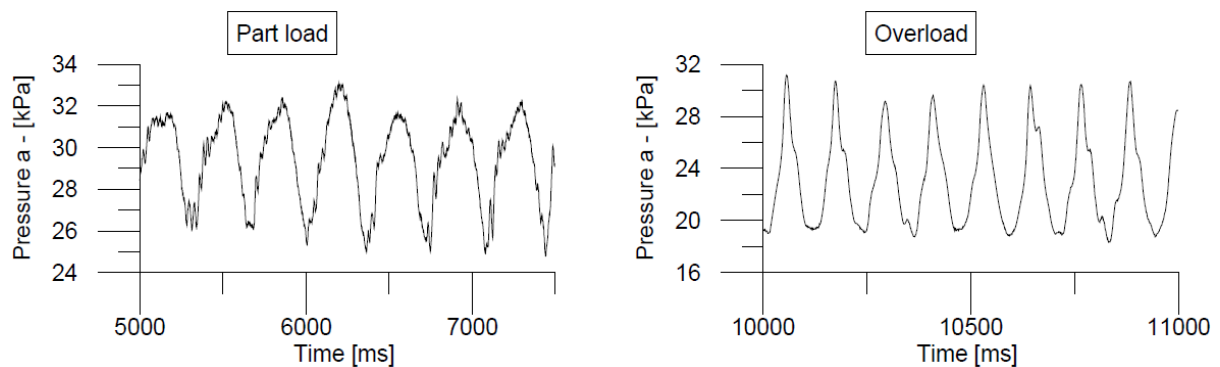

Figure 6-10 – Part and over load pressure spikes [14]

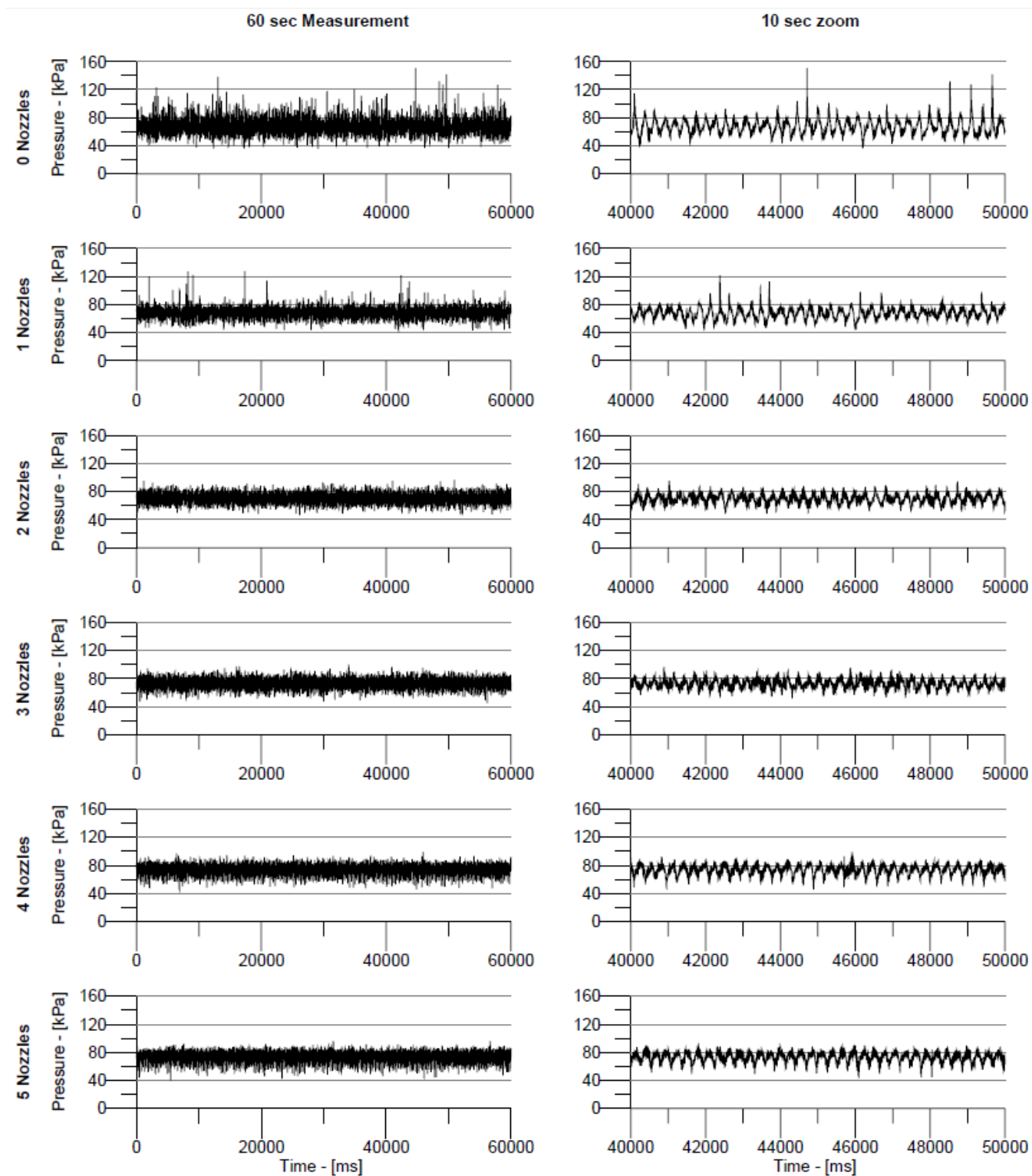It is stated that the injection gave similar results as adjusting the inlet flow speed but with power loss as a side effect [**14**]

Figure 6-11 – Draft tube pressure at Skarsfjord running at 43% load with different number of activated nozzles [14]

6.1.2.5 Svorka

See Table 6-7 for a short summary of the Svorka power plant.

Owner	Statkraft
Location	Surnadal municipality, Møre og Romsdal
Installed capacity	25MW
Water head	260m
Turbine	Francis
Turbine power	25MW
Rotational speed	600rpm
Annual production	101GWh

Table 6-7 – Svorka power plant

This facility has newly been equipped with the water injection system and little data is available for analysis of the results. The distinctive half load problems characterized by Francis turbines is however clearly visible in the draft tube pressure measurements seen in Figure 6-12 below.
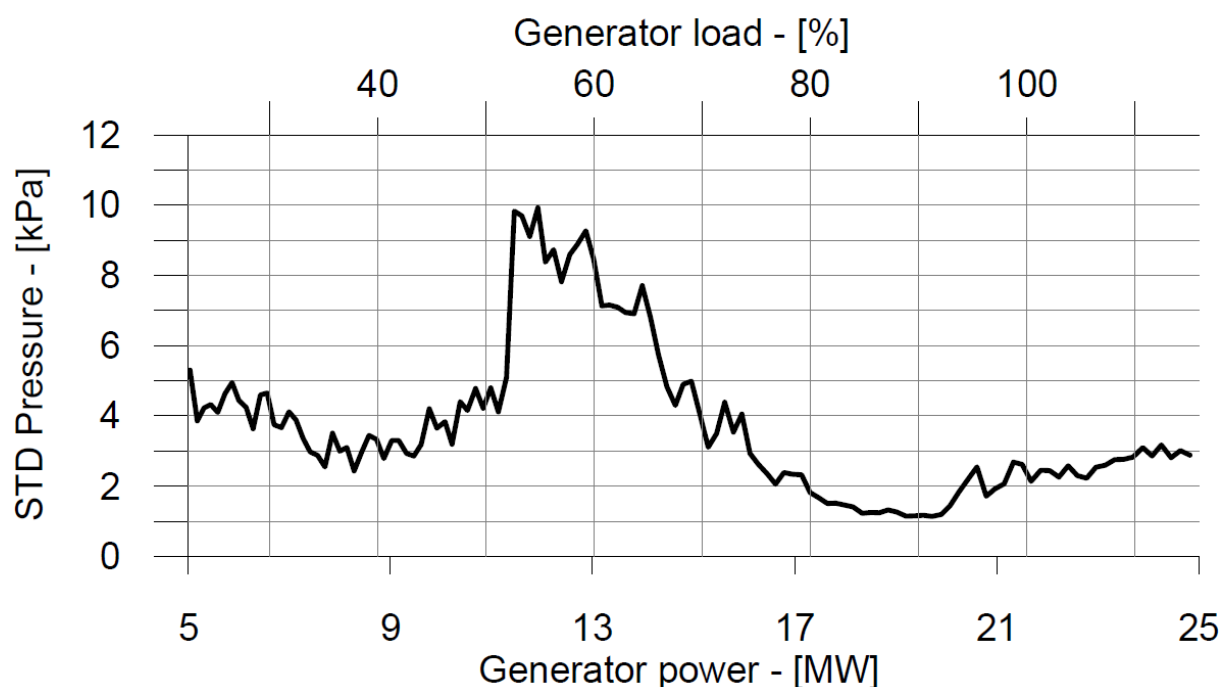

Figure 6-12 – Svorka draft tube pressure measurements as a function of power output [14]

Newly produced results from this facility can be used to gain further understanding about cavitation reduction effects of water injection system.

6.2   Economic summary

Members of the European Union can receive electric certificates if making investments that is increasing production in renewable energy sources. Installation of the investigated systems could give an increase in production which is justified to receive energy certificates, increasing the production income from the facility during the coming 15 years. This economic aid is available to the year end of 2035, making 2020 the last year of implementation that can fully benefit from full certificate period.

This tradeoff in efficiency is always present when operating outside the BEP but can be compensated by either increased energy production or producing at increased energy prices. The most profitable scenarios resulting from implementation of these techniques are related to increased total production or peak capacity. There are also possible profits related to reduced maintenance costs and increased equipment life time and reliability. But economic results related to increased reliability are assumed to be less significant due to large prediction uncertainties and the fact that reliability increase exerts a considerably smaller economic influence in comparison to that of changes in efficiency, peak or total production often does during just a fraction of the equipment lifetime.

The investigated power plants Lövhöjden and Ålviken are producing electricity at peak hours and are usually stopped during the nights. Lövhöjden already has an compressed air injection system that is used during startup and stop. There is no minimal flow required to be passed through these facilities so water can be saved until next price peak.

Since Lövhöjden has experienced problems at startup and stop it might be desirable to run this facility at lower loads instead of shutting it off at low price times. This might have a positive effect on the life time expectancy but is time restricted due to loss in revenue and the small downstream reservoir.

In general Jämtkraft does not have problems utilizing streams needed to be passed according to water rights judgments. Producing at overcapacity would be the most interesting results to invest in. The overload flow pattern differs from the part load and there is very scarce information available about results in this region, however there are some indications that this can be possible using fluid injection also. But in this scenario investments are not eligible to receive electricity certificates and there would be utilizing water resources with less efficiency. The yield would be due to increased marketable power during price peaks on the electrical energy market.

No flow statistics were investigated as initially planned; this was planned with assumptions that increased production could be achieved at some of their facilities by utilizing spill water effectively.

6.2.1 Air injection

At the case study no central aeration system was achievable but the costs are roughly estimated to around 500 000SEK.

It was found by V. TÜRKMENOĞLU that central air injection increased the annual production by 4,752GWh at Darca-1, Ordu Province in Turkey by successful vortex optimization. This facility is equipped with a generator rated 56MVA and a Francis turbine rated 49,5MW. It was only able to produce power at 44MW due to large vibrations within the alternator and turbine bearings. After installation of the air injection system it was possible to run the turbine at full discharge with a decrease of 27,68% in radial vibration. No investigation on life cycle is made, however the decrease in vibrations is thought to have a positive effect on the life cycle of the runner as well as the generator- and turbine-bearings. [**19**]

It has been shown that draft tube aeration using baffles for increased suction at Lloyd Shoals, Georgia has increased the annual production by about 1.6GWh by trading off 2-3% efficiency when the system is activated. The aeration system has made it possible to utilize lower flows such as the water rights-judgment of about $11\frac{m^3}{s}$. [**26**]

The many production stops related to the aeration system in Itaipu [**22**] acts as an important reminder that special care should be taken when installing the system at a specific facility.

6.2.2 Water injection

At the case study, price of the water injection system was estimated by M. Kjeldsen to 550 000NOK, which includes an estimate of 100 000NOK in work costs carried by local technicians and power plant personnel

Present day exchange rate between NOK, SEK, USD and Euro is presented in Table 6-8 below.

NOK	SEK	US Dollar	Euro
1000kr	1114,90kr	167,76$	123.06€

Table 6-8 – Exchange rates 2014-05-25 normalized to NOK

On site work performed by local mechanics/personnel includes cutting holes in the draft tube cone, mounting of nozzle system piping, welding of connection heads and of nozzle system piping, mounting of various transducers, cable installation and assembling of automation cabinet.

To reduce costs, the regulation valve is omitted and the estimated nozzle flow of 85l/s may be achieved using a throttling valve or orifices instead. Several parts are independent of installed capacity and the injection system price per installed power increases for smaller units.

At the Skibotn power plant the total investment cost for the nozzle system, including installation and development, amounted to about one million NOK. Increased earning attributed to the nozzle system 2010 was estimated to over eight million NOK. The past years this investment has increased profits by around three to four million NOK annually.

6.3 Case study

If fluid injection is to be installed, first measurements should be carried out to get more information about what kind of flow phenomena and problems that are present. These measurements could be carried out by mounting strain gauges on runner blades, pressure transducers in the penstock and draft tube periphery or by measuring location variations in bearings, runner or shaft.

Since no water is required to be passed at these facilities there is no noticeable production increase to be predicted. The main positive effect seen today that could be contributed to these facilities by implementation of an operating range broadening fluid injection system, is the increase in life expectancy due to reduced number of starts and stops.

In this situation there is only an expectation of annual production decrease related to implementation of either fluid injection technique and since no production increase is foreseen, the possibility of obtaining electricity certificates is eliminated. The possible profitability due to decrease in maintenance costs will quickly become challenged by the decrease in profitability due to wasteful usage of the water resources.

At flows through Lövhöjden amounting to about a third of the nominal flow, it is possible to have Ålviken shut off between price peaks of about fifteen hour periods. But Ålviken would then need to run at full capacity during four-five hours longer then Lövhöjden in order to prepare for such a scenario to be possible to occur again, making synchronization with price peaks harder to achieve.

There could be many possible solutions of how to schedule the operation plans of these facilities in accordance with the market but it most certainly complicates the planning process without giving any certain gain by doing so.

Losses accumulate in time with high degree of certainty and profits related to reduced maintenance costs are with a low degree of certainty. The economic result will most likely be negative. One way to depict the operating costs is seen below

$$Operation\ cost = \sum_{i=0}^{n} \Delta\eta_i P_i C_{e,i} \Delta t_i$$

i represents an individual operating point

n is the number of operating points available

$\Delta\eta_i$ is change in efficiency from BEP due to system running at operating point i

P_i is the power output at operating point i

$C_{e,i}$ is the average energy price during operation at operating point i

Δt_i is the time period concerned for each individual operating point i

To achieve accuracy in this calculation the sum should be divided into smaller sums each representing individual price intervals at each operating point. Smaller integration will provide with higher accuracy. A time dependent trend is present and the effect that usually has the largest diversity between plants and impact on the operation revenue is the installed production capacity.

7   Analysis, discussion and conclusions

The investment cost is not very plant dependent but the results of the techniques definitely are, hence the focus should be put on facilities with poor fuel usage or operational problems and relatively high power rating. Facilities with larger capacity will in general have shorter pay back times and might be interesting to run at overload.

Both fluid injection techniques has proven able to significantly alter the flow conditions, something that becomes desirable in bad operating points and undesirable otherwise due to the accompanied loss in efficiency. This suggests that there is a good chance that problematic situations due to deleterious flow effects at specific operating points can be improved by either of the techniques.

When using air injection, a suction method removes the need of a compressor but might require structural inserts such as fins to be mounted in order to decrease the under pressure further. When injecting water the most efficient source seems to be from the pressurized penstock water which might entirely eliminate the need for a pump. System adjustability makes it possible to operate them only when their effects are desired.

Hydraulic efficiency can in many cases be improved but the overall efficiency is mostly decreased with fluid injection systems active, only in some really badly exposed operating points can a higher efficiency be achieved and this is mainly due to terrible efficiencies at these points. If the flow problem is due to interchanging neighboring flow patterns, the effect from fluid injection is thought to be much larger than if the flow is in a stable flow pattern.

It is hard to model and predict results with accuracy and the specific solution should be fitted and adjusted to the problem experienced, making fluid injection techniques superior to fixed inserts in the subject of adjustable flow control. Installation of injection systems should be preceded by measurements to identify present problems and prepare for a tuning and feedback system. Systems are tuned individually to each facility.

Water injection seems to have a better potential in general at reducing pressure surge effects, but air injection might be structurally easier and are able to mitigate frequencies of pressure peaks, hence may also make it possible to access specific operation points that otherwise are exposed to dangerous flow effects.

Generally Jämtkraft do not suffer losses in production capability related to water spillage at their power plants. This is either because of installations with parallel turbines, plants with no minimal water flow required or due to small machines that already has a wide operational range. Neither do they suffer operational problems due to large water heads nor large variations in water head at their facilities. Hence there is no urgent need for any fluid injection system to be installed to ease part load operation and there is no safe economic estimates that can be made to support such an investment.

However there might be scenarios that can be more profitable to invest in, as with generator and turbine mismatch or upcoming scenarios when new generators are installed and the turbine gets designed to handle operation at overload. But this investment will not have the benefit of receiving additional electricity certificates from production.

Noted should be that there are possible increases in maintenance related to problems of the injection systems, hence their systems structure should be chosen carefully.

8 Proceeding work/Research/Recommendations

It would be interesting to carry out further investigations to find results on specifically mitigating Francis overload problems. And the peripheral draft tube water injection system presented in 3.4.2 could be altered to situations where overload conditions are addressed.

Also could techniques such as swirling and pulsating the injection of fluids at different locations be made in order to achieve lower amount of injected fluid, hence reducing the efficiency loss when active while providing with abilities to mitigate specific frequencies.

Further work can be made in fast responding systems for reducing random pressure pulsations using acoustics and morphing membranes.

Reliability estimates can be aided by statistics gathered on affected equipment parts life time at similar facilities with and without installed injection systems.

9 Appendix

[1] Artist unknown, Sabin Mathew gave rights (accessed 2014.05.22). Learnengineering.org. [Online]. https://3.bp.blogspot.com/-6MCsceTvHpg/Us6A4CQJSeI/AAAAAAAAC4Y/GA_ZGZuIZC4/s1600/Stay_guide_vanes.png

[2] Robert C. Chanaud, "Observations of oscillatory motion in certain swirling flows," *Journal of Fluid Mechanics*, vol. 21, pp. 111-127, March 1965.

[3] Voitto Kokko and Jouni Ahtiainen, "Ageing Due to Start-stop cycles and Frequent Regulation in Lifetime Estimation of Hydro Turbines and Generators," Grenoble, Aptril 9-11, Presentation 2014.

[4] Einar Kobro, "Measurement of Pressure Pulsations in Francis Turbines," Faculty of Engineering Science and Technology, Trondheim, PhD 2010.

[5] P. Dörfler, "Low-Frequency Phenomena in Swirling Flow," in *Flow-Induced Pulsation and Vibration in Hydroelectric Machinery*.: Springer-Verlag London, 2013, ch. 2, pp. 33-59.

[6] Tony Lee Wahl, "DRAFT TUBE SURGING HYDRAULIC MODEL STUDY," Department of Civil Engineering, Fort Collins, Colorado, Thesis 1990.

[7] Kari Haugan, "Trykkpulsasjoner i Francisturbiner," Institutt for energi og prosessteknikk, Trondheim, 2007.

[8] Pål Henrik Enger Finstad, "Secondary Flow Fields in Francis Turbines," Dept. of Energy and Process Engineering, Norway, Trondheim, Doctorial thesis 2012.

[9] Sébastien Alligné, Florine Paraz, Christian Landry, and François Avellan Andres Müller, Determination of Hydroacoustic Draft Tube Parameters by High Speed Visualization during Model Testing of a Francis Turbine, October 26-28, 2011.

[10] Oak Ridge National Laboratory, "Best Practice Catalog - Francis Turbine Aeration," Hydropower Advancement Project, Doylestown and Oak Ridge, 2011.

[11] Paul Koeller, "Draft tube aeration with check valves," Grant US4142826 A, Mar. 6, 1979.

[12] P March, "Hydraulic and Environmental Performance of Aerating Turbine Technologies," EPRI, Palo Alto, California, Proceedings of EPRI/DOE Conference on Environmentally-Enhanced Hydropower Turbines: Technical Papers Report No. 1024609, Dec 2011.

[13] Muntean, Ciocan, Nennemann Susan-Resiga, "Jet Control of the Draft Tube Vortex Rope in Francis Turbines at Partial Discharge," 23rd IAHR Symposium, Yokohama, 2006.

[14] Håkon Hjort Francke, "INCREASING HYDRO TURBINE OPERATION RANGE AND EFFICIENCIES USING WATER INJECTION IN DRAFT TUBES," Trondheim, Ph.D 2010.

[15] Håkon Hjorth Francke, "FUNDAMENTAL STUDIES OF SWIRLING FLOWS USING PITOT MEASUREMENTS," NTNU- Dept. of Energy and Process Engineering, Norway, Trondheim,

2009.

[16] H. Grein, "Vibration phenomena in francis turbines; their causes and prevention," in *Tokyo symposium 1980*, Tokyo, 1980.

[17] Constantin Tanasa, "Flow-Feedback Method for Mitigating the Vortex Rope in Decelerated Swirling Flows," *Journal of Fluids Engineering*, vol. 135, June 2013.

[18] Waplans mekaniska verkstads AB. (1988, June) Ålvikens kraftverk Turbinuppställning snitt A-A.

[19] VELİ TÜRKMENOĞLU, "The vortex effect of Francis turbine in electric power generation," *Turskish Journal of Electrical Engineering & Computer Sciences*, no. 21, pp. 26-37, Dec. 2012.

[20] Richard Fraser et al, "Improvements to Self-Venting Francis Turbines," Qubëc, 2004.

[21] Benoît PAPPILLON, "METHODS FOR AIR ADMISSION IN HYDROTURBINES," Lausanne, Symposium Proceedings 2002.

[22] Lucas Rafael Hara Motta, "PERFORMANCE ANALYSIS OF AN AERATION VALVE AND ITS PROTECTIONS OF A GENERATING UNIT IN ITAIPU HYDROELECTRIC POWER PLANT," 22nd International Congress of Mechanical Engineering, Ribeirão Preto, 2013.

[23] J. J. Gibberd, "Diagnosis and solution of severe hydro-mechanical vibrations following the upgrading of a 30MW UK hydro station," in *Conference on Refurbishment and Upgrading of Hydro Plants*, October 1997, pp. 25-38.

[24] R. Susan-Resiga, V. Câmpian, C. Dumbravă, A. Cuzmoş S. Muntean, "IN SITU UNSTEADY PRESSURE MEASUREMENTS ON THE DRAFT TUBE CONE OF THE FRANCIS TURBINE WITH AIR INJECTION OVER AN EXTENDED OPERATING RANGE," Calcutta Institute of Engineering and Management, Calcutta, 2013.

[25] Dalhaug, O. G. and Brandåstrø, B, "Virkningsgrad og falltapsmålinger ved Skarsfjord Kraftverk," VKL2005/5,.

[26] Lawrence B. Moore Jr. (2009, Jan.) Hydroworld.com (accessed 2014.05.22). [Online]. http://www.hydroworld.com/articles/hr/print/volume-28/issue-2/feature-articles/water-quality/increasing-dissolved-oxygen-with-a-draft-tube-aeration-system.html

[27] Ole Gunnar Dahlhaug, "A study of swirl flow in draft tubes," Divison of Thermal Energy and Hydropower, Trondheim, Doctorial thesis 1997.