Influence of draft tube water injection system on cavitation behaviour in a full-scale Francis turbine with visual access

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Abstract. This paper describes the results of a comprehensive and ongoing project to control unsteady fluid-dynamic behaviour and associated effects at Svorka hydro power plant (25 MW, 260 m, 600 rpm), operated by Statkraft in Norway. This Francis unit had an original air admission system installed on the draft tube wall and turbine shaft. However, these systems did not perform satisfactorily to prevent high intensity pressure fluctuations due to vortex rope at part load. To mitigate them, a complementary draft tube water injection system, designed by Flow Design Bureau AS (FDB), was installed in 2010. Moreover, the runner suffered from cavitation pitting on the blades and a measuring campaign with several accelerometers and an acoustic emission sensor concluded that the unit was susceptible to high load cavitation erosion. Given the complexity of the turbine flow, it was decided to install four transparent acrylic glass windows on the draft tube, allowing for visual access to the runner blades and outlet flow. To evaluate the influence of the draft tube injection system on the cavitation behaviour, a series of measurements of cavitation intensity were carried out. High frequency data from the sensors were processed with demodulation techniques at various expected modulation frequencies, particularly the blade passing frequency and the frequency of the draft tube vortex rope. Furthermore, the pressure pulsations were measured and quantified with pressure sensors on the draft tube wall. The results indicate that draft tube water injection has little or no effect on the measured cavitation intensity in the runner. However, other aspects of the machine, including the seasonal and daily variation of the submergence level, must be taken into consideration. In conclusion, it appears that additional long-term observations are needed to clarify the global dynamic behaviour along the entire operating range.

1. Introduction

With the increased demand for flexibility in electricity production, Francis turbines are operated more outside the best efficiency point (BEP). Thus, off design operation leads to loss of efficiency and an increased risk of deleterious pressure pulsations and cavitation [1].

Pressure pulsations in the draft tube at part load operation are caused by the rotating vortex rope (RVR). The frequency of the draft tube pressure pulsations, known as the Rheingans frequency, is normally found between 0.2 and 0.4 times the runner rotational frequency [1]. Other pressure pulsations in Francis turbines are due to rotor-stator interaction (RSI); i.e. the interaction between the rotating runner blades and the stationary guide vanes.
Air admission in the draft tube is a common method to reduce pressure pulsations by dampening the high frequency components of noise and vibration [1]. Draft tube pressure pulsations can also be mitigated by injecting high pressure water jets tangentially into the draft tube in opposite direction to the draft tube swirl at part load operation [2], [3]. Flow Design Bureau AS (FDB) has designed several injection systems, including the one installed at Svorka power plant.

Svorka power plant consists of a single turbine unit with head $H=260$ m, rotating speed $n=600$ rpm and maximum output load $P=25$ MW. The turbine has 15 runner blades and 20 guide vanes. The unit has an original air admission system installed on the draft tube wall and turbine shaft, where ambient air is aspirated into the draft tube. A draft tube water injection system was installed in 2010, which consists of three injection nozzles. Upstream the injection nozzles, the pressure is controlled by a valve to allow an injection flow rate approaching roughly 1% of the nominal turbine flow rate at $P=25$MW if draft tube pressure pulsation levels exceed pre-set thresholds when the turbine operates within pre-selected operation ranges. More specifically, the water injection system is automatically activated for part load operation for approximately 30-60 % of nominal power. Results from measurements after installation showed that the water injection system successfully reduced draft tube pressure pulsations at part load operation [3], as shown in Figure 2.

The runner at Svorka suffers cavitation erosion on the suction side of the blades close to the trailing edge, as shown in Figure 1, which may originate from cloud cavitation detaching from the leading edge [4]. Previous measurements on Svorka power plant, without draft tube water injection, had shown that the machine is prone to high load erosive blade cavitation and that the draft tube pressure pulsations propagate upstream the runner [5]. Hence, it was confirmed that the draft tube dynamics influenced the working conditions of the runner.

For research purposes, four acrylic glass windows were installed in the draft tube wall, as shown in Figure 3, to be able to visually inspect the cavitation during operation. A complete cavitation monitoring system was installed in order to correlate the obtained results with the actual cavitation conditions observed inside the runner and draft tube. Moreover, the effect of the draft tube injection system on the measured cavitation intensity was investigated and the injection system was operated manually in the full operating range of the turbine. During all the tests, air was admitted to the draft tube through the shaft and the draft tube wall.

![Figure 1](image1.png)

**Figure 1.** Cavitation erosion on blade close to trailing edge at Svorka runner.

![Figure 2](image2.png)

**Figure 2.** LOESS regression curves of draft tube pressure standard deviations showing the reduction of pulsations at installation of water injection system in 2010.
2. Experimental set-up

The experimental set-up was based on the previous measurements on Svorka reported by Escaler et al. [5] as shown in Figure 4. Accelerometers of the type B&K 4397A were placed radially and axially on the turbine guide bearing (AC TGB1 and 2) and on the guide vane shaft (AC GV). The acoustic emission sensor, Kistler AE - PC T5125, was located on the turbine guide bearing (AE TGB). Additionally, the penstock and draft tube pressures were registered with UNIK 5000 pressure sensors (PTX 5072-TA-A1-CA-H0-PA, industrial accuracy, 0-2.5 bar).

The signals were recorded using a National Instruments (NI) cDAQ 9184 chassis and LabVIEW software. The accelerometers were sampled at a frequency of 51.2 kHz and their outputs were recorded with a NI 9234 IEPE module. The acoustic emissions were measured with a NI 9205 module and sampled at 150 kHz. The pressure and guide vane opening signals were registered at a frequency of 1000 Hz with a second NI 9205 module with a 499 Ω resistance. At least two time segments of 20 seconds were recorded for approximately every steady operating point throughout the whole operating range of the unit from 1 up to 25 MW.

The visual observations were carried out with a GigE Vision Manta G-319 camera. Stroboscope lights were synchronized with the runner rotating speed and used to trigger the camera.

3. Signal processing

As in [5], the raw times signals were band-passed filtered between 20 and 25 kHz, and a Hilbert transform was applied to obtain the envelope functions. But in the current study, the modulation strength at the RSI frequency, \( f_{RSI} = 200 \text{ Hz} \), was determined by calculating the standard deviation, \( \sigma_{RSI} \), of the bandpass filtered envelope function between \( f_{RSI} \pm \Delta f \) with \( \Delta f = 0.5 \text{ Hz} \). Finally, the noise floor of the envelope function was subtracted to \( \sigma_{RSI} \). This floor level was determined by using the same approach as for calculating \( \sigma_{RSI} \) but with frequency thresholds between 161-189 Hz and 211-239 Hz, and thus giving \( \sigma_{Noise,L} \) and \( \sigma_{Noise,H} \). As a result, the cavitation intensity level, \( I \), was calculated as:

\[
I = \sigma_{RSI} - \left( \frac{n_{x,RSI}}{n_{x,Noise}} \right)^{1/2} \cdot \frac{1}{2} \left( \sigma_{Noise,L} + \sigma_{Noise,H} \right)
\]
where, $n_{RSI}$ and $n_{Noise}$ represent the number of spectral components contained within the bandpass thresholds used, i.e. $n_{RSI} = \frac{2 \cdot \Delta f}{t_s} + 1$, $n_{Noise} = \frac{189 - 161}{1/t_s} + 1 = \frac{239 - 211}{1/t_s} + 1$, where $t_s$ is the sampling period, here typically 20 s.

### 4. Results

The visual observations confirmed that a considerable amount of air was admitted to the draft tube through the turbine shaft. As a result, a vortex column of air was present in the draft tube centre axis as shown in Figure 5 at all operating points, growing with operation outside the BEP. At part and full loads, the column of air extended almost to the draft tube wall and made visual studies close to impossible.

![Image](image1.jpg)

**Figure 5.** View of the runner and output flow through the man-hole window during operation (photograph by Statkraft).

Based on previous results predicting the risk of erosive blade cavitation at high load [5], visual studies were carried out from 19 MW up to maximum load. For all the operating points, von Karman vortex shedding from the blade trailing edges was observed. As full load was approached, it was possible to see cloud cavitation collapsing close to the eroded regions of some blades at their suction side. Clear images of erosive blade cavitation and of trailing edge vortex cavitation can be seen for output loads at 21 and 23 MW in the photographs shown in Figures 6 and 7. In Figure 6, the draft tube air vortex can also be seen.
Figure 6. Flow visualization at 23 MW showing von Karman vortex shedding, cloud cavitation and draft tube air vortex.

Figure 7. Flow visualization at 21 MW (photograph by Rainpower).

In Figure 8, the spectra of the draft tube pressure measurements without draft tube water injection show a distinct Rheingans frequency of around 2.4 Hz for part load operation, which is 24% of the runner rotation frequency of 10 Hz. For higher loads above the BEP, a lower frequency of 0.4 Hz is also apparent. This frequency corresponds to the natural frequency of the elastic wave to the free surface in the surge chamber. In order to quantify the effect of the water injection system on the Reingans frequency, the standard deviations of the draft tube pressures in the band between 1.5 and 4 Hz are compared for measurements with and without water injection in Figure 9.

Figure 8. Spectra of draft tube pressure pulsations without water injection.

Figure 9. Standard deviations of draft tube pressures filtered between 1.5 and 4 Hz.

Figure 10 shows the amplitude modulation spectra from 0 to 250 Hz of the turbine guide bearing vibrations filtered in the band from 20 to 25 kHz for the full operating range with (left) and without (right) water injection. A clear peak is found around 0.4 to 0.6 Hz for high load operation. Conversely, there is no modulation peak around the Rheingans frequency for part load operation.

A modulation at the RSI frequency from a rotating point of reference, fRSI = 200 Hz, can be seen at higher loads in all the accelerometers and the acoustic emission sensor, which corresponds to the guide vane passing frequency. Meanwhile, only the guide vane acceleration shows the RSI frequency from a stationary point of reference at 150 Hz. Amplitude modulations of turbine guide bearing accelerations
are shown in Figure 11 for frequencies from 195 to 205 Hz. It can be confirmed that $f_{RSI}$ modulation is significant for higher loads, but it is not present at part load operation.

**Figure 10.** Amplitude modulation spectra of vibration acceleration at turbine guide bearing from 0 to 250 Hz.

**Figure 11.** Amplitude modulation spectra from 195 to 205 Hz of turbine guide bearing acceleration. Highlighted lines correspond to operation points of 18, 20 and 22 MW.

The cavitation intensity level calculated from the turbine guide bearing vibration, $I$, is presented in Figure 12 for operation with and without water injection. The results indicate high cavitation intensity at high loads from 18 to 22 MW and at full load of 25 MW, with a minimum around 23 MW. Results from the rest of accelerometers show similar trends as already found in previous measurements [5].
Figure 12. Cavitation intensity indicator based on standard deviations of turbine guide bearing accelerations (filtered from 20 to 25 kHz and modulated at 200 Hz) with and without water injection and LOESS regression curves.

5. Discussion

The air admitted through the turbine shaft made the visual studies very challenging. It formed a large air bubble in the draft tube centre which grew as the turbine was operated further away from BEP. Unfortunately, it was not possible to evaluate the total size and amount of air and how far downstream it extended. This large amount of air will obviously greatly affect the draft tube conditions by dampening pressure pulsations and modifying operational conditions.

Photographs of the runner showed von Karman vortex shedding from the runner trailing edges for most operating points with visual access not blocked by the central air column. These vortices are a sign of a poorly designed trailing edge and can contribute to a lower efficiency, but they are not a source of erosive cavitation. Cloud cavitation collapsing on the blade suction side close to the leading edge was also observed, which is responsible of the erosion. The number of runner blades with identified cavitation clouds increased with operating load, which is in agreement with the evolution of the cavitation intensity estimator and showing maximum values at high load operation.

It was demonstrated that modulation amplitudes at \( f_{\text{RPS}} \) of turbine guide bearing vibrations are slightly decreased when the injection system is operated, as shown in Figure 11. Similar trends could be seen for guide vane accelerations and acoustic emissions. However, the general noise level was increased for some areas of operation. This might be due to the fact that the injected water also suffers cavitation as it enters the draft tube. Evaluation of cavitation intensity by standard deviation values of band passed signals, Figure 12, showed that the injection system had little influence regarding the detected cavitation. However, the location of the peak amplitudes was shifted towards lower generator power levels, i.e. the high intensities measured at 20MW are significantly reduced by injection, but the same levels appear at 18MW.

The same tendency was found in the measured pressure pulsations at installation of the injection system, shown in Figure 2. The peak was shifted left towards lower powers. This was expected given the fact that water injection modifies the swirl of the draft tube flow [2]. This tendency is not evident for the current results presented in Figure 9. Now, the draft tube injection system does not appear to have the same effect on dampening the pressure pulsations as in the previous measurements. A possible reason for this is the uncertainty and variation regarding the surface level of the river, which has not been measured during neither the previous nor the current study. Another factor is the deposit of smaller rocks and sedimentation at the draft tube outlet. A variation in the submerge of the turbine will determine
the flow rate of air into the draft tube. It is believed that the effect of the water injection system will differ for various air admission flow rates.

6. Conclusion
The results obtained during tests of the Francis turbine at Svorka indicated that the draft tube water injection system had negligible effect on the measured cavitation intensity in the runner. After gaining visual access to the draft tube flow, it was evident that the air admitted through the runner shaft had to be taken into consideration to evaluate the water injection system performance. As well as being a source of uncertainty, the air in the centre of the draft tube made the visual studies more difficult and impossible at some operation conditions. Therefore, a repetition of the experiments presented here is suggested with the air admission system completely closed off. Furthermore, a long-term measurement campaign will be initialized at Svorka to monitor the effects of the seasonal conditions on cavitation intensity. In addition to the set-up of sensors described above, a continuous measurement of the water level in the outlet will also be included.

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