Pressure Pulsation in a High Head Francis Turbine Operating at Variable Speed

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Abstract. This paper presents the preliminary work of the master thesis of the author, written at the Norwegian University of Science and Technology. Today, many Francis turbines experience formation of cracks in the runner due to pressure pulsations. This can eventually cause failure. One way to reduce this effect is to change the operation point of the turbine, by utilizing variable speed technology. This work presents the results from measurements of the Francis turbine at the Waterpower Laboratory at NTNU. Measurements of pressure pulsations and efficiency were done for the whole operating range of a high head Francis model turbine. The results will be presented in a similar diagram as the Hill Chart, but instead of constant efficiency curves there will be curves of constant peak-peak values. This way, it is possible to find an optimal operation point for the same power production, were the pressure pulsations are at its lowest. Six points were chosen for further analysis to instigate the effect of changing the speed by ±50 rpm. The analysis shows best results for operation below BEP when the speed was reduced. The change in speed also introduced the possibility to have other frequencies in the system. It is therefore important avoid runner speeds that can cause resonance in the system.

Keyword: Francis Turbine, Variable Speed, Pressure Pulsation, Hill Chart, Hydro Power

1. Introduction
The electrical grid is a complex system, which is coupled with different types of energy sources as hydro, wind and solar. Because of the flexibility that the Hydropower turbines offers, it is used to stabilize the grid by changing operating point, and therefore the power output [3]. The result of this is that the turbine more often is running off-design. Off-design phenomena such as power swings, rotating vortex rope and part load pressure pulsations can drastically reduce a runners operating life [5]. One of the problems with Francis turbines today is the formation cracks in the runner due to pressure fluctuations, and the industry if facing problems with both new and old Francis turbines [2]. It is therefore of interest to find methods for reducing the effects of pressure fluctuations, and prolong the lifetime of the runner. One potential method of doing this, is by introducing variable speed technology. This enables us to change operation point by changing the speed of the runner to where pressure pulsations are at its lowest.

The present work aims to investigate the pressure pulsations for the whole operating range, and to understand how pressure pulsation varies with different operational conditions. A total of 269 different operational points have been measured, from guide vane opening of 1 degree to 14 degree (full opening). By analysing these different operational conditions, it is possible to find out where to operate the turbine were the pressure pulsations are at its lowest. Six operational points, Full Load...
(FL), High Load (HL), Best Efficiency Point (BEP), Part Load (PL), Minimum Load (ML) and Speed-No-Load (SNL) has been chosen for further analysis to check how the peak-peak values and frequency spectrum of pressure pulsation varies when the speed is changed by ±50 rpm.

1.1. Variable Speed Operation
A Francis turbine is designed for fixed speed and for one best efficiency point. The speed of the turbine is predetermined by the combination of pole pairs in the generator and the grid frequency. Therefore, turbine power output is controlled by changing the guide vane opening and thereby water discharge. By utilizing a frequency converter, together with the synchronous generator, it is possible to operate with variable speed. The generator is then decoupled from the grid, and free to operate at different speeds [5]. The turbine will be more flexible, when it can regulate both speed and water discharge, and can avoid operational conditions with cavitation problems and high pressure pulsation. The drawback is additional converter losses that must be considered.

2. Laboratory Setup and Methods

2.1. Francis Model Test Rig
Measurement were conducted at the Francis model test rig located at the Waterpower laboratory at NTNU. The test rig was operated by using an open loop configuration, as seen in Figure 1. The water is pumped from the basement reservoir to a channel located at the top of the laboratory. The water is then going through an upstream pressure tank before entering the turbine. Downstream the draft tube, there is a pressure tank which is used to regulate the pressure at the outlet from the runner. For this measurement the water level in the draft tube pressure tank was open to air. Water is then going back to the reservoir. The open loop configuration gives a uniform water level (≈12m) and provides same conditions for all operation points. The Francis turbine is a scaled down model (1:5.1) of the Tokke turbine. It has 14 stay vanes, 28 guide vanes and 30 runner blades (15 full length and 15 splitter blades).

2.2. Logging Program and Equipment
The measurement system is a complete setup with all the necessary equipment for calculating the efficiency (and to draw a Hill Chart), according to the IEC60193. There is also additional pressure sensors along the guide vanes, on the draft tube cone and on-board the runner, according to Figure 2 and Figure 3. The draft tube pressure sensors (PTDT5, PTDT7, PTDT13, PTDT17) are mounted on the draft tube cone. Pressure sensors along guide vanes (PTGV1-PTGV6) is mounted on the top of the casing, and the on-board pressure sensors (PTR1-PTR6) is mounted between the blades on the crown. The on-board system is transmitting measurement signals via slip rings to the logging system. The logging frequency was 10240Hz for all sensors. A LabVIEW program, developed in the laboratory, was used as logging software.

Figure 1. Open loop configuration. (1) centrifugal pump, (2) and (3) open water channel, (4) upstream pressure tank (5) flowmeter, (6) generator, (7) Francis turbine, (8) downstream pressure tank, (9) water outlet.
2.3. Measurement Procedure
Measurements were done for guide vane opening from 1 degree to 14 degree opening (1, 2, ..., 14). The starting point for each guide vane opening was $N_{ED}=0.08$, and the end point was run-away speed ($\approx 0.28$). The increment between each measurement was $N_{ED}=0.01$. This gave a total number of 269 measurement points, from deep part load to full load. All operational points were logged for 60 seconds.

Figure 2. Pressure sensors. GV1-GV6 along guide vanes and R1-R6 on-board the runner.

Figure 3. On-board sensors, R1-R4, and draft tube pressure sensors; DT5, DT7, DT13, DT17.

2.4. Data Analysis
MatLab were used for analysing all the measured data. Efficiency calculations for the Hill Chart was done according to IEC60193 [6]. For analysing peak-peak values of pressure data, the Histogram method was used, with a confidence level of 97% as suggested in IEC60193 [6]. The Histogram method has proven to give good results, and have been used by Gogstad in his PhD [8] and been suggested by Dörfler et.al. [7]. For the spectral analysis, Welch method was used together with a Hanning window with 50% overlap. A set of filters were applied to the pressure data to remove noise, before the data was used for analysis.

3. Results
Figure 4 shows the complete Hill Chart for the Francis turbine, from guide vane opening of 1 degree to 14 degree. The turbine would normally operate at $N_{ED}=0.18$ (333rpm), and BEP is located at $Q_{ED}=0.154$ with and maximum efficiency just above 92%. For the pressure pulsation analysis three different pressure sensors were used to obtain peak-peak values, PTDT13, PTR2 and PTGV4 (Figure 2 and Figure 3). These three sensors were chosen to investigate pressure pulsation effects in the whole turbine based on their location. Peak-peak values was calculated for all operation points, for each sensor, and are presented in a similar way as the Hill Chart. Instead of lines of constant efficiency, there is lines of constant peak-peak values. By doing this, it is easier to identify were pressure pulsation have high values, and which operational areas that should be avoided. In these diagrams, the 97% confidence level is used, as suggested in [6]. Other values may be more correct, and 99% was used by Gogstad [8], but this was not investigated further in this work. Figure 5 shows the results from the draft tube sensor, PTDT13. Diagrams for the other sensors can be found in the Appendix. Peak-peak values are normalised, based on the BEP value. The absolute values are given in Table 2.

Six points were chosen for further analysis; SNL, ML, PL, BEP, HL and FL. Table 1 shows more detailed information on the different operational point. Each point was compared with another
operational point, with the same power output, were the speed is reduced and increased by 50 rpm, to investigate how the pressure pulsation varies with a change in speed. The different points can be seen as dots in Figure 5 (along N_{ED}=0.155, N_{ED}=0.1795 and N_{ED}=0.208). The lines that goes through the different points are lines of constant power. Table 2-4 shows how peak-peak values varies when the speed was changed.

![Hill Chart](image)

**Figure 4.** Hill Chart for the whole operation range. Guide vane opening from 1 degree to 14 degrees. N_{ED} varies from 0.08 to run away speed.

![Pressure Pulsation Diagram, PTDT13](image)
Figure 5. Pressure Pulsations diagram for PTDT13, draft tube sensor. Peak-peak values are normalised based on BEP value and are calculated based on 97% confidence level. The BEP value is calculated to be 2.39kPa. The marked points is used for further analysis, and the lines that goes through them is lines of constant power.

Table 1. Detailed information for operational points used in further analysis

| GV opening [degree] | Efficiency [%] | NED [-] | QED [-] | Speed [rpm] | Mech Power [kW] |
|---------------------|----------------|---------|---------|-------------|-----------------|
| ML                  | 4              | 84.9    | 0.1798  | 0.067       | 338             | 9.04            |
| PL                  | 7              | 91.3    | 0.1795  | 0.111       | 336             | 15.9            |
| BEP                 | 10             | 92.2    | 0.1795  | 0.155       | 335             | 22.2            |
| HL                  | 12             | 92.2    | 0.1795  | 0.178       | 334             | 25.4            |
| FL                  | 14             | 90.7    | 0.1795  | 0.201       | 333             | 28.0            |
| SNL                 | 1              | 40      | 0.1795  | 0.02        | 340             | 1.3             |

Table 2. Peak-peak values for sensor PTDT13, 97% confidence level. The last two columns show the relative change in peak-peak between normal speed and changed speed. All values are in kPa.

| Normal speed (≈333rpm) | Reduced speed (≈286rpm) | Increased speed (≈386rpm) | Relative change when reducing speed | Relative change when increasing speed |
|------------------------|-------------------------|---------------------------|-----------------------------------|------------------------------------|
| ML                     | 2.82                    | 1.62                      | 3.86                              | 0.57                               | 1.37                        |
| PL                     | 2.16                    | 1.62                      | 3.04                              | 0.75                               | 1.41                        |
| BEP                    | 2.39                    | 2.39                      | 2.95                              | 1.0                                | 1.23                        |
| HL                     | 2.52                    | 2.13                      | 3.29                              | 0.85                               | 1.31                        |
| FL                     | 3.12                    | 3.1                       | -                                 | 0.99                               | -                           |
| SNL                    | 1.88                    | 1.31                      | 2.74                              | 0.70                               | 1.46                        |

Table 3. Peak-peak values for sensor PTGV4, 97% confidence level. The last two columns show the relative change in peak-peak between normal speed and changed speed. All values are in kPa.

| Normal speed (≈333rpm) | Reduced speed (≈286rpm) | Increased speed (≈386rpm) | Relative change when reducing speed | Relative change when increasing speed |
|------------------------|-------------------------|---------------------------|-----------------------------------|------------------------------------|
| ML                     | 2.96                    | 2.56                      | 3.73                              | 0.86                               | 1.26                        |
| PL                     | 2.87                    | 2.7                       | 3.51                              | 0.94                               | 1.22                        |
| BEP                    | 2.37                    | 2.76                      | 2.59                              | 1.16                               | 1.09                        |
| HL                     | 2.5                     | 2.54                      | 4.22                              | 1.02                               | 1.69                        |
| FL                     | 3.1                     | 2.82                      | -                                 | 0.91                               | -                           |
| SNL                    | 1.15                    | 0.78                      | 1.59                              | 0.68                               | 1.38                        |

Table 4. Peak-peak values for sensor PTR2, 97% confidence level. The last two columns show the relative change in peak-peak between normal speed and changed speed. All values are in kPa.

| Normal speed (≈333rpm) | Reduced speed (≈286rpm) | Increased speed (≈386rpm) | Relative change when reducing speed | Relative change when increasing speed |
|------------------------|-------------------------|---------------------------|-----------------------------------|------------------------------------|
| ML                     | 4.1                     | 2.86                      | 4.84                              | 0.70                               | 1.18                        |
| PL                     | 2.86                    | 2.95                      | 4.05                              | 1.03                               | 1.42                        |
| BEP                    | 3.04                    | 3.02                      | 3.91                              | 0.99                               | 1.29                        |
| HL                     | 3.05                    | 3.32                      | 4.44                              | 1.09                               | 1.46                        |
| FL                     | 3.35                    | 3.29                      | -                                 | 0.98                               | -                           |
| SNL                    | 4.82                    | 3.19                      | 5.91                              | 0.66                               | 1.22                        |
Frequency spectrum analysis was conducted for the six different points and the ones with changed speed. This provides information on which flow phenomena causes pressure fluctuation in the turbine, and which is contributing the most. By using reduced frequencies, it is possible to compare the results when the speed is changed, and see if there are changes in the occurring frequencies. Pressure data was analysed with Welch method in MatLab. Figure 6 shows the result from spectrum analysis for sensor PTGV4 at High Load operation. Figure 7 shows the results for PTR2 at High Load operation.

![Frequency spectrum, sensor PTGV4 at High Load](image)

**Figure 6.** Frequency analysis of pressure data from PTGV4 at HL, for normal speed and changed speed. The blade passing frequency is most dominant with a frequency of 30 times the rotational frequency ($f$). There is also an effect due to the splitter blade that causes frequencies at $15*f$. Stochastic pulsations occur in the low frequency region.

![Frequency spectrum, sensor PTR2 at High Load](image)

**Figure 7.** Frequency analysis of pressure data from PTR2 at HL, for normal speed and changed speed. The guide-vane-passing frequency is most dominating ($28*f$). There is also stochastic pulsations in the low frequency region.

4. Discussion
The three different pressure pulsation diagrams show different behaviour for the pressure pulsations. The draft tube pressure pulsation clearly shows a trend towards lower peak-peak values for lower speed and discharge, while the pulsation around the guide vanes and on-board the runner shows lowest values at BEP and around an area where the speed is reduced. There are also indications that it is possible to find optimum operation points for minimal pulsations, especially when reducing the speed, but there will be a give-and-take between lowest peak-peak values in the different part of the turbine.
The diagrams from PTGV4 and PTR2 show more similarities than the one for PTDT13. This make sense because Rotor-Stator Interaction (RSI) is the most dominating phenomena for both sensors (Figure 6 and Figure 7). It is therefore important to figure out what is most damaging for the turbine, and find optimal operation based on this.

From Table 2-4 we can see the result from changing the speed (±50 rpm) from six operation points. There was no effect at BEP for the three sensors. This is as expected since this is the design point. Also, when the speed is increased, the pressure pulsations are increasing for all operation points. On the other hand, if the speed was reduced, pressure pulsations dropped for almost all the sensor at all operation points, and the reduction is highest for operation below BEP. In the draft tube, the pressure pulsations are reduced with 25%, 30% and 30% for PL, ML and SNL. While on-board the runner (PTR2), the same reduction is 0%, 29% and 34%, and 6%, 14% and 32% for PTGV4. Pressure pulsations for operation above BEP was not strongly affected by the reduction in speed, and peak-peak values on-board the runner increased with 9% at HL. It should be said that speed change is not limited to ±50 rpm, (15% change in speed), and different speed may give even lower pressure pulsations.

Frequency analysis was performed for all operation points, to investigate which pulsation phenomena that occurred for the different points, and to find out how the change in speed affected the frequencies. Figure 6 and Figure 7 shows the results from HL for PTGV4 and PTR2. For these two sensors, the RSI was found to be most dominant for all the operation point, except at part load operation, where the draft tube vortex rope was dominating. Also the effect of the splitter blades was found in the analysis, which was half the blade-passing frequency, along the guide vanes. For PTDT13, the pressure pulsations was dominated of a frequency between 1.45-1.8 times the runner frequency, combined with stochastic fluctuations. At part-load operation, the vortex rope was dominating the pressure pulsation. This proves some of the challenges that follows variable speed operation. Many of the frequencies are speed depended, such as RSI and the draft tube vortex rope. A change in speed will therefore introduce many more frequencies that potentially can cause resonance in the system.

5. Conclusion
An experimental investigation of a high head Francis turbine was conducted to investigate pressure pulsation for the whole operation range. The purpose of this was to see it is possible to reduce the effect of pressure pulsation by utilizing variable speed, and thereby avoid operational problems and crack formation in the runner. A Hill Chart was constructed, and pressure pulsation were analysed for three different sensors. Three pressure pulsation diagrams were created, similar to a Hill Chart but with lines of constant pressure pulsations (peak-peak values). Six points were chosen for further analysis to see how the pressure pulsation varied with a speed change of ±50 rpm, but with the same power output.

Increasing the speed resulted in higher peak-peak values for off-design operation, while reducing the speed resulted in reduced pressure pulsation in most of the cases. The highest reduction in pressure pulsation was found for operation below BEP, for all three sensors. The maximum reduction was found for Speed-No-Load, were the peak-peak values was reduced by more than 30%. The investigated points were chosen arbitrarily, and the pressure pulsation diagrams gives indication that other operational points would give even lower peak-peak values. RSI was found to be most dominating in the upper part of the turbine, together with the vortex rope at curtain part load operation points. These pressure fluctuations are speed dependent and will change according to the speed. It is there important avoid runner speed that can cause resonance in the system.
Appendices

A.1 PTGV4 Pressure Pulsation Diagram

Peak-peak values are calculated with 97% confidence level. All the values are normalised with respect to the BEP value. The BEP value is calculated to be 2.37kPa. Normal operating is along $N_{ED}=0.18$. 
A.2 PTR2 Pressure Pulsation Diagram

Peak-peak values are calculated with 97% confidence level. All the values are normalised with respect to the BEP value. The BEP value is calculated to be 3.04kPa. Normal operating is along $N_{ED}=0.18$. 


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