Selection and Optimization of Sensors for Monitoring of Francis Turbines

David Valentín*, Alexandre Presas, Carme Valero, Mònica Egusquiza and Eduard Egusquiza

Center for Industrial Diagnostics and Fluid Dynamics (CDIF), Universitat Politècnica de Catalunya (UPC), Av. Diagonal, 647, ETSEIB, 08028, Barcelona, Spain.
david.valentin@upc.edu

Abstract. With the current demand of flexibility to hydraulic turbines, these are working under off-design conditions more than ever. Under these conditions different complex hydraulic phenomena appear, especially in Francis turbines, affecting the machine stability as well as reducing the useful life of its components. Hence, it is desirable to detect in real-time these hydraulic phenomena to assess the operation of the machine. In addition, the position and type of sensor to detect these phenomena is a key point for the monitoring of Francis units. In this paper, a large medium-head Francis turbine was instrumented with several sensors such as accelerometers, proximity probes, strain gauges, pressure sensors and a microphone. Results obtained with the different sensors in different locations are compared to know which hydraulic phenomenon is detected with every sensor. Furthermore, different signal analysis techniques are also compared. With this information, monitoring systems can be optimized with the most convenient sensors, locations and signal analysis techniques, reducing its difficulty to install and economic cost.

1. Introduction

One of the most trending topics in hydropower nowadays is the flexibility of the units [1]. They have to compensate the intermittent generation capacity of wind or solar power, thus they need to work more and more in off-design conditions with more transient events than in the past. Hydraulic turbines, and specially Francis turbines, suffer from dynamic problems when they are working out of their BEP (Best Efficiency Point). These dynamic problems are of different origin and magnitude depending on the operating point and the design of the runner. Estimating the potential damage of every operating point to the different components of the turbine is therefore of paramount importance from the maintenance point of view.

Different hydraulic phenomena occur in the different operating regimes of Francis turbines. Cavitation, turbulence, vortex rope are some of the hydraulic phenomena that usually appear in this kind of machines. Additionally, those phenomena can lead to hydro-acoustic or mechanic resonances [2–4], amplifying their effects to the different components of the turbine. The nature of every phenomenon is different, so its detection is also different, and different sensors, locations or signal analysis techniques have to be used in every case.

Monitoring systems based in vibration [5,6] are usually installed in hydropower plants. However, they just normally monitor overall levels in stationary parts such as bearings or displacement in the shaft. Optimizing those monitoring systems for the detection of the different hydraulic phenomena is
therefore very important. With the minimum number of sensors placed in the right locations and with the adequate signal analysis technique, all the hydraulic phenomena that occur in a Francis turbine can be detected.

The selection and optimization of type and number of sensors is discussed in the present paper. For this purpose, a large Francis turbine prototype (444 MW) has been studied in detail. Different type of sensors, such as accelerometers, proximity probes, strain gauges, pressure sensors and microphone, have been installed in different locations of the machine in order to detect all of the phenomena occurring the turbine. Furthermore, different signal analysis techniques have been applied to the each of the sensors in order to improve and optimize the actual monitoring systems installed in the hydropower plants. The results discussed in this conference paper have been previously published in [7].

2. Experimental investigation

2.1. Prototype characteristics
A large Francis turbine have been used with a rated power of 444 MW. The study of this turbine is a part of the European project Hyperbole (FP7-ENERGY-2013-1) [8]. The rotating speed of the machine is 128.6 rpm (2.14 Hz). It has 20 guide vanes and 16 blades in the runner. More characteristics of this turbine can be found in references [6,9,10].

2.2. Instrumentation
Several sensors were installed in both stationary and rotating parts of the machine. Pressure sensors were installed in the draft tube, spiral casing, penstock and runner blades. Strain gauges were installed in the runner blades and in the shaft. Proximity probes were used to measure the displacement in the turbine bearing and in the generator bearing. Accelerometers were located in the bearings, head cover, guide vanes, spiral casing, draft tube and in the shaft. Additionally, one microphone was located near the draft tube. Electrical parameters such as power, voltage and current were also monitored simultaneously. A picture of the installed sensors can be seen in Figure 1.

The total number of sensors installed was 67. In this study, only one type of sensor for location has been selected, reducing the number of sensors to compare to 16. Almost all of signals were acquired at a sampling frequency 4096 Hz, but some accelerometers and the microphone were acquired at higher sampling rate (65536 Hz) in order to apply high frequency demodulation techniques to them. Table 1 shows the sensors used for study, their location, direction and acquisition frequency.

| Type               | Nomenclature | Location      | Direction | Acquisition Frequency |
|--------------------|--------------|---------------|-----------|-----------------------|
| Accelerometer      | AT           | Turbine bearing | Radial   | 65,536 Hz             |
| Accelerometer      | AG           | Generator bearing | Radial   | 4096 Hz               |
| Accelerometer      | AGA          | Thrust bearing | Axial     | 4096 Hz               |
| Accelerometer      | ADT          | Draft tube    | Radial   | 65,536 Hz             |
| Accelerometer      | ASC          | Spiral casing | Radial   | 4096 Hz               |
| Accelerometer      | AHC          | Head cover    | Axial     | 65,536 Hz             |
| Accelerometer      | AGV          | Guide vane    | Radial   | 65,536 Hz             |
| Proximity probe    | DT           | Turbine bearing | Radial   | 4096 Hz               |
| Proximity probe    | DG           | Generator bearing | Radial   | 4096 Hz               |
| Pressure sensor    | PDT          | Draft tube    | Radial   | 4096 Hz               |
| Pressure sensor    | PSC          | Draft tube    | Radial   | 4096 Hz               |

Table 1. Sensors used and their characteristics. Source [7].
2.3. Testing procedure
The turbine was operated for 5 minutes in different points in its whole operating range. The head for all the measurements was constant except for the last point in the full load regime, where it was decreased to the reach the overload instability.

3. Signal analysis
Three different signal analysis techniques were used to detect the different phenomena with every sensor: FFT (Fast Fourier Transform), RMS (Root mean square) values and demodulation analysis. Those methods are compared in the results section.

4. Results
Four different regimes of operation were identified for this Francis turbine: DPL (Deep Part Load), PL (Part Load), HPL (High Part Load) and FL (Full Load).
4.1. Deep Part Load
This regime is identified from 0 to 0.286 P/P_{rated}. The main hydraulic phenomena in this regime is the high level of turbulence. This turbulence is of random nature and origin, which means that is able to excite natural frequencies of the structure randomly. In this case, it is clear that a natural frequency of the rotating train is excited, and its amplitude is higher in the generator bearing. Figure 2 shows the FFTs of the accelerometers in the generator bearings and Figure 3 the RMS values classified in different frequency bands.

![Figure 2. Turbulence exciting shaft natural frequencies. Source [7].](image)

4.2. Part Load
This regime is identified from 0.286 to 0.608 P/P_{rated}. The main hydraulic phenomena that is occurring in this regime is the vortex rope. This vortex rope is formed by an asynchronous (radial) component and a synchronous (axial) component. At some point (P/P_{rated}=0.59) it coincides with a hydraulic natural frequency and hydraulic resonance occurs. The asynchronous component is well captured with the proximity probes in the turbine bearing and the synchronous component with all the pressure sensors. These results are shown in Figure 4. Accelerometers are able to detect also the synchronous component but after applying demodulation techniques (see Figure 5).

![Figure 3. RMS values for different frequency bands. a) Radial accelerometer in the generator bearing. b) Axial accelerometer in the generator bearing (f_r is the rotating frequency). Source [7].](image)

4.2. Part Load
This regime is identified from 0.286 to 0.608 P/P_{rated}. The main hydraulic phenomena that is occurring in this regime is the vortex rope. This vortex rope is formed by an asynchronous (radial) component and a synchronous (axial) component. At some point (P/P_{rated}=0.59) it coincides with a hydraulic natural frequency and hydraulic resonance occurs. The asynchronous component is well captured with the proximity probes in the turbine bearing and the synchronous component with all the pressure sensors. These results are shown in Figure 4. Accelerometers are able to detect also the synchronous component but after applying demodulation techniques (see Figure 5).
4.3. High Part Load
This regime goes from 0.540 to 0.946 \( P/P_{\text{rated}} \). For this Francis turbine, in this regime there are three different kind of hydraulic phenomena: Cavitation, a mechanical resonance of the runner and a hydraulic resonance of the hydraulic circuit.

The cavitation is detected though high levels of RMS values in the accelerometers, especially in high frequency bands (see Figure 6). The high value of vibration at the guide vane suggests that it could be inlet cavitation due to the high head during the tests.

A mechanical resonance in the runner is confirmed with the strain gauges located in the blades. In this case, the third harmonic of the RSI coincides with a natural frequency of the runner. This natural frequency of the runner is probably affected by the inlet cavitation mentioned above, and this is why it is only excited in this operating regime. In the turbine bearing, this phenomenon is also detected (see Figure 7).

A hydraulic resonance at 1.3 the rotating frequency of the runner is also detected in this regime. This resonance is detected in all pressure sensors as well as in the axial accelerometer in the generator bearing, which means that it induces an axial movement to the machine. These results are shown in Figure 8.
Figure 6. RMS values for different frequency bands. a) Accelerometer in the head cover. b) Accelerometer in the guide vane.

Figure 7. FFT of a strain gauge in the runner (a) and the turbine bearing (b).

Figure 8. Detection of the high part load resonance. a) Pressure sensor in the spiral casing. b) Axial accelerometer in the generator bearing.
4.4. Full Load
This regime is defined for \( P/P_{\text{rated}} > 1 \). In this case, the hydraulic phenomena occurring is the overload instability associated to a full load vortex rope. This vortex rope is of axial natural and it produces very large power swing in this machine (see reference [11]). This phenomenon is found at \( P/P_{\text{rated}} = 1.086 \) and it can be detected in all the pressure sensors, torque, power fluctuation (see Figure 9) and in the accelerometers when applying demodulation techniques (Figure 10).

![Figure 9. Detection of the overload instability. a) Pressure sensor in the draft tube. b) Torque in the shaft.](image)

![Figure 10. Detection of the overload instability through demodulation analysis (band 13-15 kHz). a) Accelerometer in the draft tube. b) Microphone in the draft tube.](image)

4.5. Summary
All the results for the detection of the different phenomena with different sensors are presented in Table 2. This table gives the information of which sensors are the most useful to detect the different phenomena and therefore to optimize the number and locations. It is observed that the accelerometer of the turbine bearing, the accelerometer of the head cover and the accelerometer of the guide vane and the one in the shaft are the ones that detect more phenomena (7 of 8). The asynchronous component of the part load vortex rope can only be detected with the displacement sensor in the turbine bearing or the strain gauges in the runner.
Table 2. Summary of the detection of every phenomenon with every sensor and technique. Source [7].

| Operating regime | T/P | Phenomenon | Detection Technique | Synchronization Frame | Sensors |
|------------------|-----|------------|---------------------|-----------------------|---------|
|                   |     |            |                     | Acceleration | Displacement | Pressure | Power | Sound | Torque | Strain | Acc. |
|                   |     |            |                     | AT | AG | AGA | ADT | ASC | ASC | ACV | DT | DC | PDT | PBC | PBY | MDT | T | PC | ASH |
| Deep Part Load    | 0.286 | Turbulence exciting rotating train natural frequency | FFT | No | No | (2.4)6 | No | (2.4)6 | No | (4.4)6 | No | No | No | No | No | No | (2.4)6 | No |
|                   |     |            | Demodulation | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No |
|                   |     | Vortex rope–oscillations component | FFT | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No |
|                   |     |            | Demodulation | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No |
|                   | 0.297 | Cyclone Hop–synchronization component | FFT | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No |
|                   |     |            | Demodulation | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No |
|                   | 0.59 | Hydroturbulence resonance | FFT | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No |
|                   |     |            | Demodulation | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No |
|                   | 0.625 | Cavitation | FFT | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No |
|                   |     |            | Demodulation | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No |
| High Part Load    | 0.705 | Stator resonance | FFT | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No |
|                   |     |            | Demodulation | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No |
|                   | 0.849 | Hydroturbulence resonance | FFT | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No |
|                   |     |            | Demodulation | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No |
| Overload 1.0056   | 4.25 | Overside instability | FFT | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No |
|                   |     |            | Demodulation | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No | No |

| Number of phenomena detected (only the phenomena with good detection are counted) | FFT | 1 | 1 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 0 |
|                                                                             | SME | 3 | 3 | 2 | 2 | 4 | 5 | 5 | 3 | 3 | 2 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 0 |
|                                                                             | Total | 7 | 7 | 4 | 4 | 8 | 8 | 8 | 4 | 3 | 3 | 2 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 0 |

| Not detected | Poor detection | Good detection | Not applicable |
5. Conclusions

Different phenomena occurring in a large Francis turbine prototype have been detected using different type of sensors. Those sensors were located in different parts of the machine. Additionally, different signal analysis techniques have been applied to the different sensors to see if they are able to detect every phenomenon.

Sixteen different sensors in different locations have been compared for the whole range of operation of the turbine. Results show which sensors are better to detect every phenomenon and with which signal analysis technique. This permits improving the actual monitoring systems installed in hydropower plants by reducing the number of sensors.

Results show that accelerometers in the turbine bearing, head cover and guide vane are able to detect almost all of the phenomena. However, they cannot detect the asynchronous component of the part load vortex rope, which can only be detected with the proximity probes in the turbine bearing or the strain gauges in the runner.

References

1. Kougias, I.; Aggidis, G.; Avellan, F.; Deniz, S.; Lundin, U.; Moro, A.; Muntean, S.; Novara, D.; Pérez-Díaz, J.I.; Quaranta, E.; et al. Analysis of emerging technologies in the hydropower sector. *Renew. Sustain. Energy Rev.* 2019, 113, 109257.
2. Presas, A.; Valentín, D.; Egusquiza, E.; Valero, C.; Seidel, U. On the detection of natural frequencies and mode shapes of submerged rotating disk-like structures from the casing. *Mech. Syst. Signal Process*. 2015.
3. Favrel, A.; Junior, J.G.P.; Landry, C.; Alligné, S.; Andolfatto, L.; Nicolet, C.; Avellan, F. Prediction of hydro-acoustic resonances in hydropower plants by a new approach based on the concept of swirl number. *J. Hydraul. Res.* 2019, 0, 1–18.
4. Bossio, M.; Valentín, D.; Presas, A.; Martin, D.R.; Egusquiza, E.; Valero, C.; Egusquiza, M. Numerical study on the influence of acoustic natural frequencies on the dynamic behaviour of submerged and confined disk-like structures. *J. Fluids Struct.* 2017, 73, 53–69.
5. Egusquiza, E.; Valero, C.; Valentín, D.; Presas, A.; Rodríguez, C.G. Condition monitoring of pump-turbines. New challenges. *Measurement* 2015, 46, 151–163.
6. Valero, C.; Egusquiza, E.; Presas, A.; Valentín, D.; Egusquiza, M.; Bossio, M. Condition monitoring of a prototype turbine. Description of the system and main results. *J. Phys. Conf. Ser.* 2017.
7. Valentín, D.; Presas, A.; Valero, C.; Egusquiza, M.; Egusquiza, E. Detection of Hydraulic Phenomena in Francis Turbines with Different Sensors. *Sensors (Basel)*. 2019, 19, 4053.
8. Hyperbole Project HYdropower plants PERformance and flexiBle Operation towards Lean integration of new renewable Energies Available online: https://hyperbole.epfl.ch.
9. Presas, A.; Valentín, D.; Egusquiza, M.; Valero, C.; Egusquiza, E.; Presas, A.; Valentín, D.; Egusquiza, M.; Valero, C.; Egusquiza, E. Sensor-Based Optimized Control of the Full Load Instability in Large Hydraulic Turbines. *Sensors* 2018, 18, 1038.
10. Valentín, D.; Presas, A.; Valero, C.; Egusquiza, M.; Egusquiza, E. Synchronous condenser operation in Francis turbines: Effects in the runner stress and machine vibration. *Renew. Energy* 2020, 146, 890–900.
11. Valentín, D.; Presas, A.; Egusquiza, E.; Valero, C.; Egusquiza, M.; Bossio, M. Power Swing Generated in Francis Turbines by Part Load and Overload Instabilities. *Energies* 2017, 10, 2124.