Monitoring 4.0 of penstocks: digital twin for fatigue assessment

M Dreyer[1], C Nicolet[1], A Gaspoz[2], N Gonçalves[2], S Rey-Mermet[2], B Boulicaut[3]

[1] Power Vision Engineering Sàrl, CH-1025 St-Sulpice, Switzerland
[2] HES-SO Valais, CH-1950 Sion, Switzerland
[3] Electricité d'Emosson SA, CH-1920 Martigny, Switzerland

email: matthieu.dreyer@powervision-eng.ch

Abstract. In Europe, the ambitious goal of targeting at least 64% of electricity production from renewables by 2050 requires some significant increase of power network ancillary services. A general extension of primary/secondary reserves is necessary to cope with the increasing penetration of stochastic renewable energies and maintain the grid vulnerability at acceptable levels. In this context, hydropower plants are called upon to play a major role due to their operational flexibility and ability to provide ancillary services. However, the provision of these services is not without consequences for the plant, as the increase of load variations and start/stop sequences enhances fatigue problems by soliciting the penstocks faster than originally expected. Given that the fatigue wear rate can be 10x higher when ancillary services are active, it is crucial to ensure the fitness-for-service of the penstocks by proper monitoring. Nevertheless, the number of sensors along the hydraulic circuit is often very limited, so that periodic stops of the plant and inspections are necessary to assess the health of the pipes. In this paper, we present how a digital twin of the power plant, namely the Hydro-Clone system, can be used to fill this gap by enabling real-time knowledge of the transient pressures throughout the water conduits. These pressures are correlated to the stress variations using either analytical formula or finite element modelling (FEM), depending on the geometry and embedding conditions of each penstock element. The validity of this approach is demonstrated by comparing the predicted stresses with measured values in the penstock of the 200 MW *La Bâtiaz* hydropower plant, owned by Electricité d'Emosson SA. To this end, strain gages are mounted at the bottom and top of the penstock, in front of the manifold and on the penstock protection valve. The appropriate conversion of pressure to stress at the strain gage location is derived through the analysis of FEM simulations. This work shows the benefits of using a digital twin for fatigue assessment and paves the way for real-time penstocks fatigue monitoring.

1. Introduction

In the European energy roadmap 2050 [1], the *High Energy Efficiency Scenario* of the decarbonization process forecasts a share of 64% of renewable energy sources (RES) in electricity consumption, and 97% in the *High Renewables Scenario*, which includes significant electricity storage to accommodate varying RES supply even at times of low demand. These ambitious goals rely on a drastic change in the European Union electric power system, with a massive integration of non-dispatchable RES. A general increase of regulating power provision to the grid is therefore necessary to ensure load/generation balance and cope with the increasing penetration of stochastic renewable energies, while maintaining the grid vulnerability at acceptable levels. In this context, hydropower plants are called upon to play a major role for electrical power network stability thanks to their operational flexibility and their ability to provide ancillary services. In practice, the provision of these services must comply with rules defined by the country's Transmission System Operator (TSO). For instance in Switzerland, the TSO Swissgrid has the following requirements for the three main ancillary services [2]:

- **primary control**, i.e. «Frequency Containment Reserves (FCR)»: active power setpoint changes within maximum 30 s;
- **secondary control**, i.e. «Automatic Frequency Restoration Reserves (aFRR)»: power setpoint changes withing maximum 5 minutes, minimum control range of ±5 MW and minimum output power change rate of 0.5 % of the rated output power per second;

– **tertiary control**, i.e. fast «manual Frequency Restoration Reserves (mFRR)» and slow «Replacement Reserves (RR)» : power setpoint changes within 15 minutes.

However, the provision of these services is not without consequences for the plant since the frequent start and stop sequences of the machines, as well as continuous load variations, induce hydraulic transient phenomena in the water conduits, which severely stress the pipe structure. Moreover, with the modernization of control systems, hydroelectric power plants are reacting more and more quickly and are even more solicited than originally expected, leading to enhance fatigue problems. As demonstrated in the case of *La Bâtiaz* high head Pelton turbine power plant, in Switzerland, the provision of ancillary services contribute significantly to the penstock fatigue, particularly at the top of the penstock, see [3][4]. In fact, the fatigue wear rate at the top of the penstock is about 10x higher when these services are active, as illustrated in Figure 1, which compares the relative accumulated damage index along the penstock for 24h of exploitation with ancillary services (FCR+FRR) and without ancillary service provision, cf. to [3] for more details.

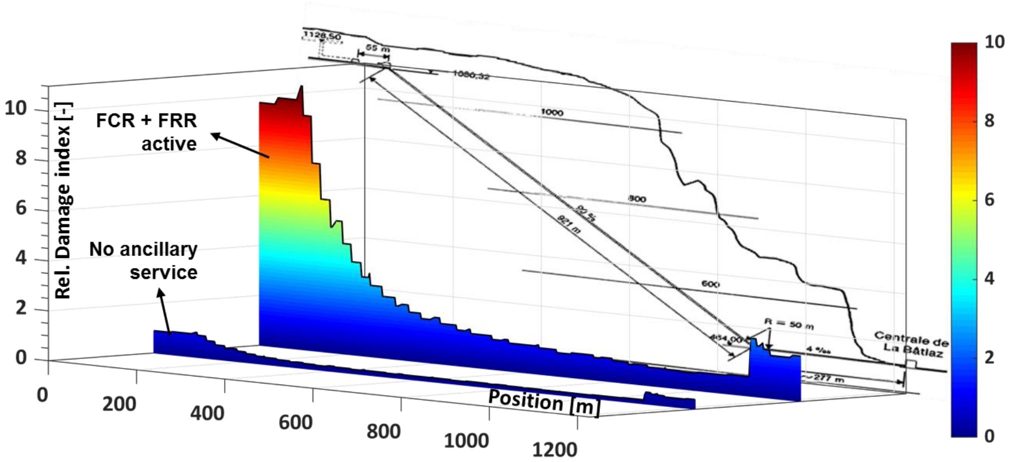

Figure 1. Comparison of the relative accumulated damage index (z-axis) along the penstock for 24 h of exploitation with ancillary services (FCR+FRR) and without ancillary service.

In the light of these results, it is crucial to ensure the fitness-for-service of penstocks by proper monitoring. Since the effective loading spectra along the penstock are the fundamental input for a fatigue evaluation procedure, it is essential to have a means of accurately and continuously determining the stresses in the pipe structure. Yet, this is a challenging task, as the number of sensors along the hydraulic circuit is often very limited due to access difficulties. In fact, the waterways of a hydropower plant are often poorly monitored compared to the turbine, as schematized in Figure 2. In addition, it is not always easy to derive the correct fitness-to-service indicators from the monitored signals, so in practice, periodic plant shutdowns and inspections are often required to assess the health of the pipes.

The use of a digital twin, such as Hydro-Clone®, can help to overcome these difficulties by replicating in real time all the pressure variations induced by hydraulic transients throughout the water conduits. The immediate benefits of this digitalization is that it allows access to the non-measured/non-measurable quantities at all times [5][6], such as pressures in the headrace tunnel and penstocks. These pressures can be correlated to the stress variations using either analytical formula or finite element modelling (FEM), depending on the geometry and embedding conditions of each penstock element. Theses stresses can then be post-processed to derive the penstock level of solicitation. In this paper, the validity of this methodology is demonstrated by comparing the stresses measured in situ with strain gages, with the values obtained by finite element analysis (FEA) or simple analytic formula, such as hoop stress equation for thin-walled cylindrical pressure vessel.

a) b)

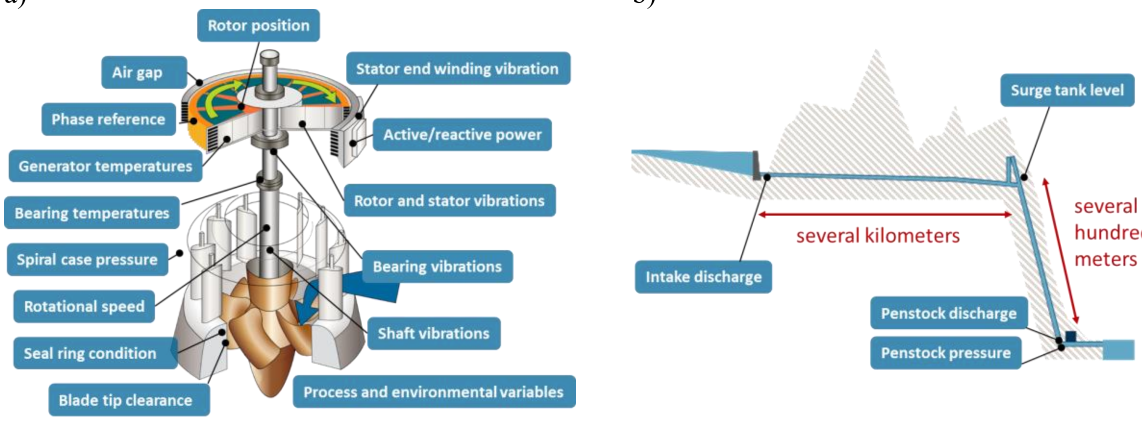

Figure 2. Schematic illustration of the difference in instrumentation density on the unit (a), relative to the rest of the waterways (b).

2. Methodology

2.1. Hydro-Clone digital twin of hydropower plant

Hydro-Clone is a digital twin of the hydropower plant (HPP), running on a standard computer located in the power plant, capable of reproducing in real-time any dynamic behaviour of the plant, with a focus on hydraulic transients [7][8]. Hydro-Clone allows continuous diagnosis of the health of an HPP by simulating the main hydraulic and electrical components behaviour of the plant using SIMSEN software driven by the appropriated boundary conditions measured in situ. The general concept of Hydro-Clone is illustrated in Figure 3. The system manages the tasks of real-time acquisition and transfer of boundary conditions and measured quantities to the SIMSEN model, as well as data processing and diagnosis of the HPP health status. A custom-built archival storage system and an associated database allow for the display and analysis of previous results. As such, the digital twin can identify unusual events, for which measurements and simulations are no longer in phase. This can be used to detect a sensor failure, but also potentially more serious events such as unintentional water hammer caused by an improper turbine shutdown sequence. Another obvious advantage of this digitalization is that it allows access at all times to the non-measured/non-measurable quantities, such as pressures and discharge, throughout the powerplant.

The schematic implementation of the Hydro-Clone in the existing measurement chain of the powerplant is illustrated in Figure 4 along with the data workflow. This comprises the data exchanged between the Hydro-Clone computer and the HPP SCADA system at a sampling rate of 10 Hz using the MODBUS TCP protocol, as well as eventual additional signals coming from other programmable logic controllers (PLC), dispatched in the powerplant. A remote access is integrated to the Hydro-Clone PC, allowing an efficient deployment and maintenance of the system. The Hydro-Clone system was installed in 2014 at the *La Bâtiaz* power plant and has been in continuous operation for more than six years. The database generated by Hydro-Clone over several years thus constitutes a valuable source of information on the operating condition of the power plant and makes it possible to quantify the impact of the different modes of operation on fatigue, as presented in the subsequent sections.

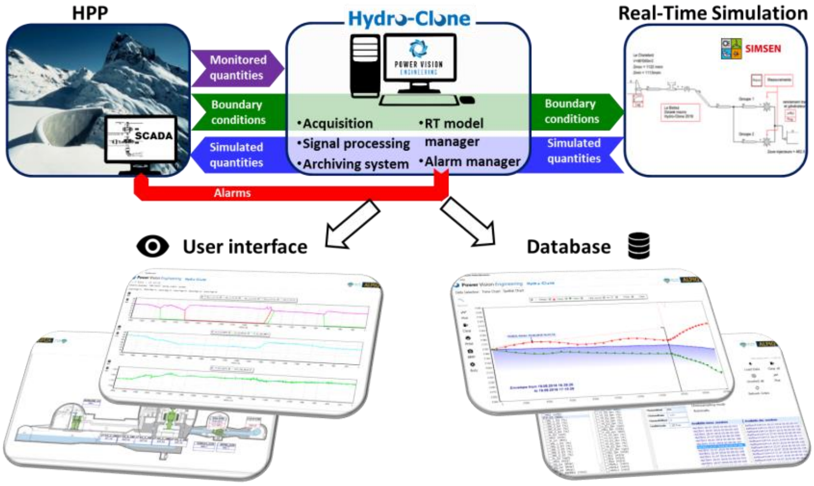

Figure 3. Hydro-Clone general concept with the illustration of the data flow exchange and visualization during real-time simulation

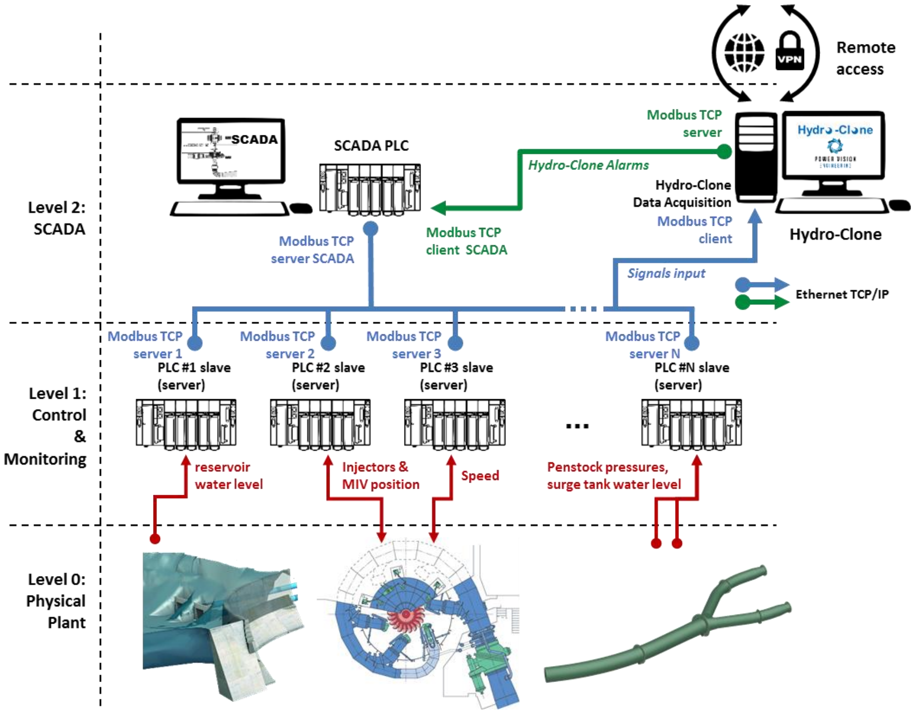

Figure 4. Schematic diagram of the implementation of the Hydro-Clone in the measurement chain of the power plant and architecture of the Modbus TCP network for data exchange.

2.2. In situ stress measurement

Stresses in the pipe have been measured in situ at the top and bottom of penstock, on the penstock protection valve and on the Y-bifurcator in front of the manifold, as illustrated in Figure 5. At both locations, a section of the pipe was instrumented with two *HBM RY81 6/350* rosette strain gages, installed on the side and on the top of the conduit respectively. The stress analysis obtained by the FEM described in the next section was used to identify the most appropriate areas to install the gages.

In order to cope with thermal expansion of the strain gages glue, mainly induced by direct sunlight at the penstock bottom, a third control gauge is used to measure specifically these thermal effects. This latter was fixed on an independent metal plate, made of the same nature as the penstock, placed next to the other strain gages. The thermally induced drift in the measured stresses are then corrected by subtracting the stress measured by the control strain gauge from the other signals. This produces a stress-corrected value, which is independent of the temperature of the glue and more representative of the actual stress in the penstock.

The Figure 6 illustrates the acquisition chain used for the stresses measurement on the penstock protection valve and Y-bifurcator manifold. In order to synchronize the measurements made at the top of the penstock with those made at the bottom, a voltage pulse of 5V is generated periodically and transmitted through some pre-existing copper wire along the penstock. This pulsed-reference signal is used to correct for any drift and offset of the internal clock of the two DAQ devices during the post-processing of the measurements.

The acquisition was performed during two full days at a maximum sampling rate of 1 kHz. For practical reasons, the sampling rate of the pressure variations simulated by Hydro-Clone are limited to 10 Hz at *La Bâtiaz* powerplant. The measured stress signals are therefore down-sampled at 10 Hz so that they can be compared with the values simulated by the digital twin. Nevertheless, as it was verified in [3], this lower sampling rate does not eliminate any significant stress fluctuations relevant for the fatigue assessment. Indeed, the only additional stress fluctuations present at 1 kHz can be considered as white noise, the small amplitude of which does not contribute significantly to the fatigue.

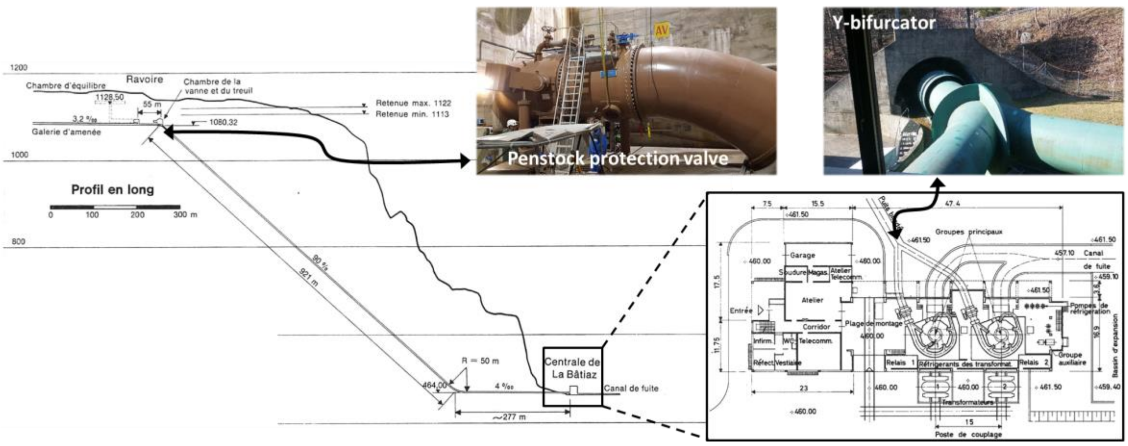

Figure 5. Sketch of the 1.2 km penstock of *La Bâtiaz* powerplant as well as detail of the manifold. The pictures illustrate the location of the penstock protection valve and Y-bifurcator where the strain gages are installed.

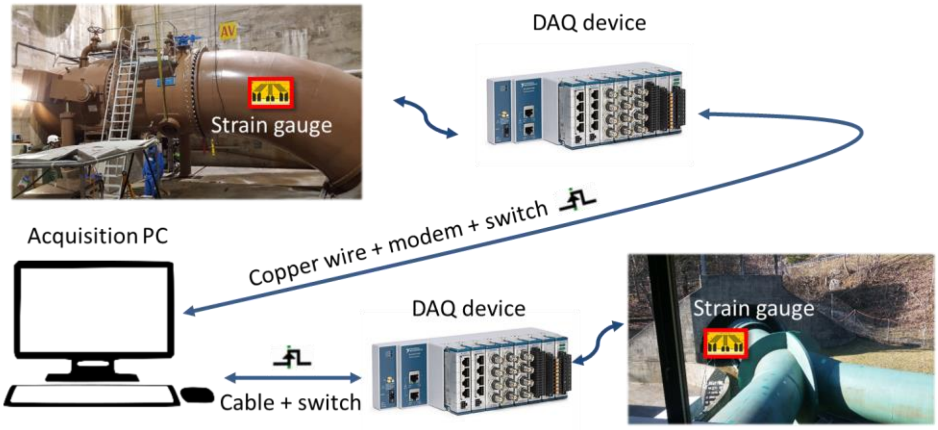

Figure 6. Acquisition chain of stresses measurement on the penstock protection valve (top of penstock) and manifold (bottom of penstock). The signals of the two strain gages are synchronized by means of a pulsed reference signal.

2.3. Finite element modelling to determine the pressure-stress relation

Finite element analysis (FEA) of the penstock protection valve, situated just downstream of the surge tank, and Y-bifurcator at the penstock bottom has been carried out in order to determine the locations of highest solicitation, using *ANSYS* software. As illustrated in Figure 7 and Figure 8, the element geometry and embedding conditions have been accurately reconstructed. The mesh of the 2.7 m diameter penstock protection valve comprises about 200'000 nodes, while the 2.4 m diameter Y-bifurcator model is composed of about 225'000 nodes. For both elements, the simulation of several load conditions was performed, yielding the equivalent Von-Mises stresses represented in the figures below for a typical load case.

By simulating the stress loads occurring for different internal pressures, it is then possible to determine the relationship between the pipe internal pressure p and stress σ, i.e. $\Delta\sigma$=f(Δp), at any point of the element. The relations between water pressure and stress calculated in place of local supports and in place of local deviations from the circular form are of a non-linear nature, which can be approximated by a polynomial regression, as done in [9]. During normal plant operation, it is however reasonable to consider that the stresses variations will be linked linearly to the pressure fluctuations experienced by the penstock, i.e., the ratio $\Delta\sigma/\Delta p$ is a constant. This approach has been applied to the penstock protection valve and manifold by computing the stress load for a pressure variation of ~4 bars, which is a typical pressure fluctuation value, that occurs several times a day in normal operation. The computed stresses at the location of the strain gages can be decomposed into its tangential and axial components, which can be used to derive the $\Delta\sigma/\Delta p$ ratio and compare it to the experimental value.

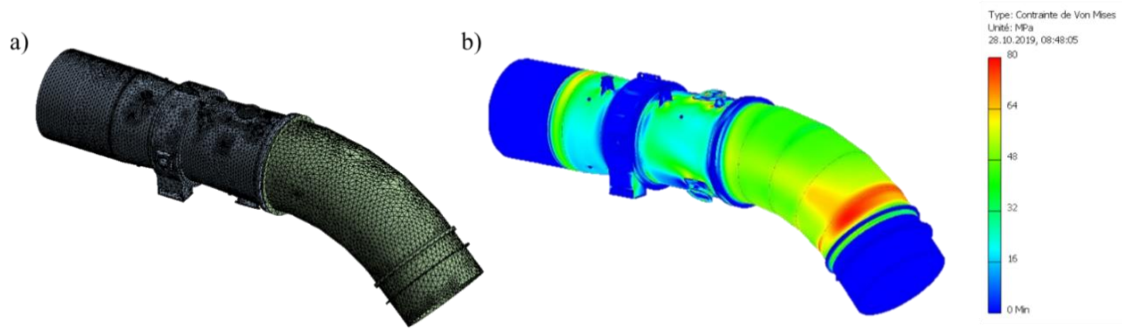

Figure 7. Mesh of the finite element model of the 2.7 m diameter penstock protection valve (a) and illustration of the calculated Von Mises stresses in case of internal pressure increase of 4 bars (b).

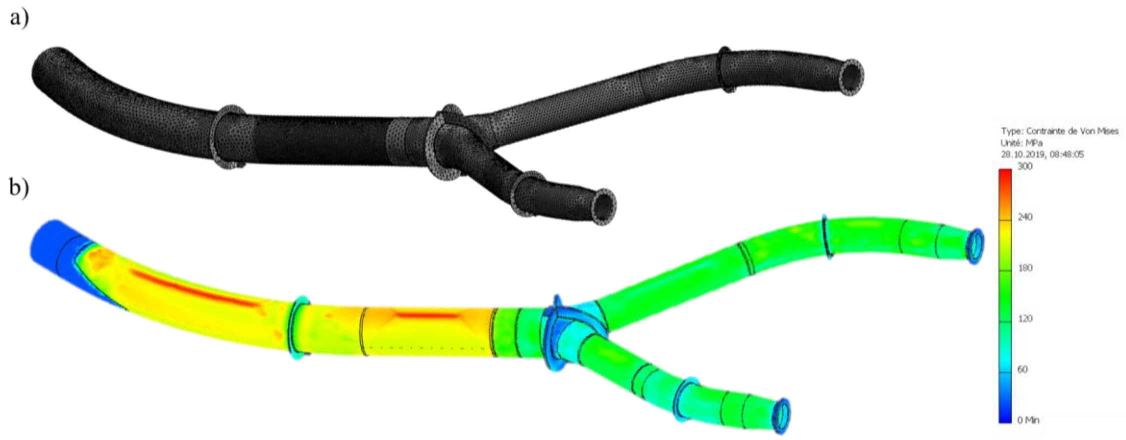

Figure 8. Mesh of the finite element model of the 2.4 m diameter Y-bifurcator (a) and illustration of the computed Von Mises stresses in case of internal pressure increase of 4 bars (b).

3. Results

3.1. Pressure-stress relation

The ability to correlate the pressure fluctuations experienced in the water pipes with the stresses in the material is a necessary conditions in order to link the simulated data from the digital twin of the hydropower plant with the fatigue assessment of the penstock. In the case of a straight section of an open-air penstock, it is fair to assume that the hoop stress equation for thin shells, also known as Barlow's formula, is valid:

$$\frac{\Delta\sigma}{\Delta \mathrm{p}} = \frac{D}{2e} \tag{1}$$

in which D and e represent the pipe diameter and thickness, respectively. The Table 1 gives these values for the penstock protection valve and Y-bifurcator at the position of the strain gages.

Table 1. Dimension of the pipe radius and thickness at the location of stress measurement

	Pipe radius [m]	Pipe thickness [m]
Top of penstock	1.350	0.0125
Bottom of penstock	1.200	0.026

For specific details where the hoop stress equation for thin shells is not valid, the general relationship between the pipe internal pressure p and stress σ at any point, $\Delta\sigma$=f(Δp), can be determined using finite element modelling (FEM) for each penstock detail, taking into account their geometry and embedding conditions. The approach described in section 2.3 was applied to the penstock protection valve and Y-bifurcator. By extracting the tangential stresses for two computed load cases with a pressure difference of ~4 bars, it is possible to determine the ratio Δσ/Δp at the location of the strain gages.

Both approaches, i.e. analytic Barlow's formula (1) and FEM extracted Δσ/Δp were compare with the experimentally measured stresses in situ. To do so, the simulated pressures extracted from the digital twin at the location the strain gages were multiplied by the best fit ratio that would reproduced the experimental values of stress. Table 2 presents the comparison of the stress-to-pressure ratio Δσ/Δp as obtained with the different approaches enumerated, i.e. the best fit of the measured strain gages values, FEM extracted ratio or Barlow's analytic formula, for both top and bottom of the penstock.

Table 2. Comparison of the pressure to stress relations as obtained with the strain gages, FEM model or thin wall hoop stress equation, for the top and bottom of the penstock.

Δσ/Δp [MPa/bar] relation	Strain gauge best fit	FEM extracted	Thin wall hoop stress
Top of penstock	10.821	10.840	10.800
Bottom of penstock	4.450	4.553	4.615

As it can be observed, the FEM extracted ratio and Barlow's formula give both a Δσ/Δp ratio very close to the experimental best fit value, both at the penstock protection valve and Y-bifurcator. This shows that both approaches achieve very satisfactory results in transposing pressure fluctuations into stress at the location of the strain gages. This similarity between the result obtain with the simple hoop stress equation for thin shells and FEM computation was to be expected, as the location of the strain gages was carefully chosen to be on a part of the penstock which would behave like a straight section of an open-air penstock. Another noteworthy point is the fact that the Δσ/Δp ratio is much higher at the top of the penstock than at the bottom. As a consequence, for an identical pressure fluctuation, the stress variation will be greater in the penstock protection valve than in the Y-bifurcator. This can be explained by the fact that the upper part of the shaft has been designed for lower static pressures, therefore constructed with thinner plates than the lower part, which is subject to high pressure.

Figure 9 shows a comparison of the measured stress at the penstock top and bottom, obtained with the strain gages at a sampling rate of 10 Hz, and the value simulated by Hydro-Clone using the thin wall hoop stress equation for stress pressure-to-stress conversion. The agreement between the measured and simulated values is remarkable since the stress values simulated by the digital twin correspond almost perfectly to the strain gages values at the top and bottom during the several hours of comparison. In addition, it can be observed that the bottom of the pipe, which is close to the turbines, has more high-frequency fluctuations that tend to dampen as they propagate through the pipes toward the penstock protection valve. Nevertheless, and as expected, for an equal pressure variation, the top of the penstock experiences a greater stress variation than the bottom.

As evidenced by these results, FEA can be used for approximating the relationship between internal pressure and stress at the strain gauge location with good accuracy. It is therefore reasonable to use the same approach to derive the Δσ/Δp ratio at other locations, particularly in critical regions where stress concentrations occur. For instance FEA can be used to determined stresses near the welded details and extrapolated to the hot spots of the component where a the fitness-for-service needs to be evaluated. For the portions of the pressure shaft with steel lining embedded in concrete and surrounded by the rock mass, advanced models of pressure shafts can also be used to deduce the stress within steel lining considering the surrounding effects and anisotropic rock mass, see [10][11].

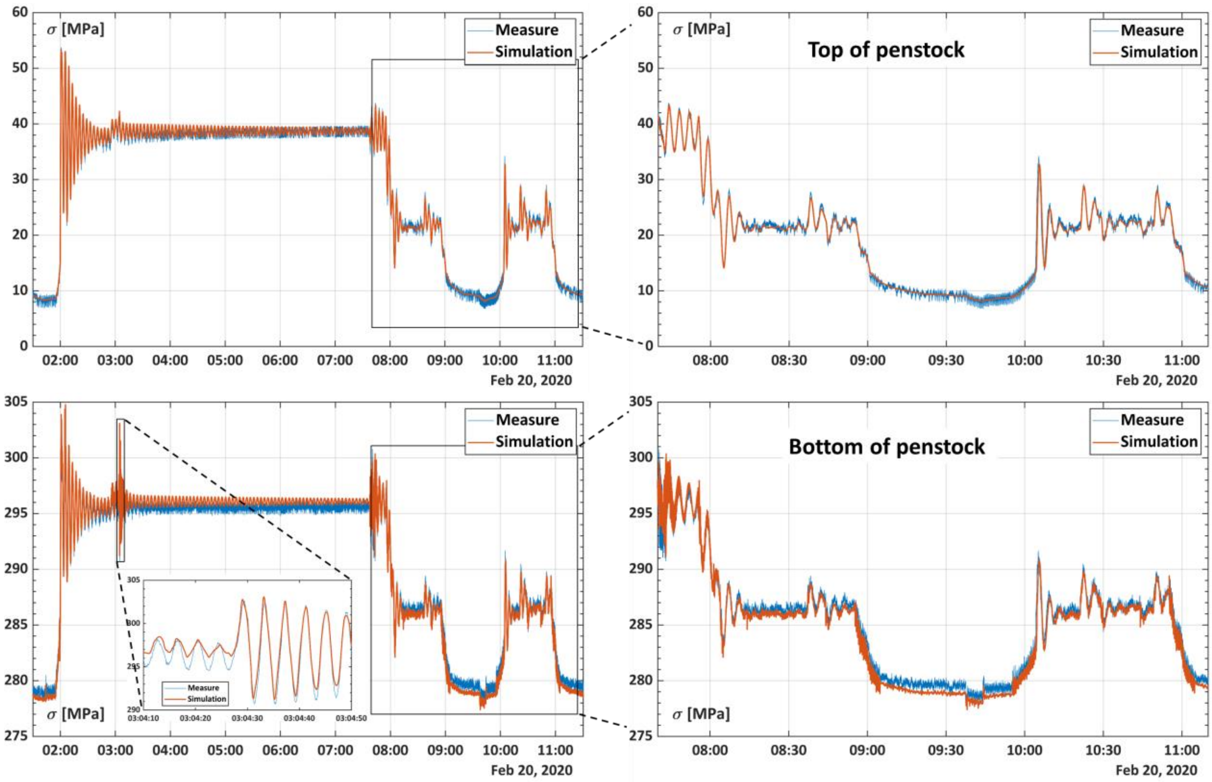

Figure 9. Comparison of the measured stress (blue line) with the simulated value computed by Hydro-Clone (orange line). Top: stresses on the penstock protection valve (top of the penstock). Bottom: stresses on the Y-bifurcator (bottom of the penstock).

3.2. Impact of ancillary services provision on penstock fatigue

The previously described approach to correlate the pressure fluctuations with the stresses in the penstock has been exploited to assess the penstock level of solicitation during two typical days with different operating modes of the power plant: with the provision of FCR & FRR ancillary services and without ancillary service provision. The overall methodology of the penstock fatigue assessment follows the procedure described in detail in [3]. basically, the Hydro-Clone system provides real-time knowledge of transient pressures along a number of nodes along the penstock. These transient pressures are then converted into stress variation using the relations in Table 2. Following the ASTM standard [12], the number of fatigue cycles contained in the load-time history is determined by applying a rain flow cycle counting algorithm. The cumulative damage for each penstock segment is then tallied using Miner's rule in combination with the appropriate S-N curve (also known as Wöhler's curve), in accordance with BS7910 standard [13], yielding the damage index profile along the penstock.

Figure 10 shows the accumulated damage index at the penstock protection valve and Y-bifurcator with and without the provision of ancillary service, using the relations in Table 2. All results are presented in terms of relative damage index, i.e. the maximum damage along the penstock obtained for the case without ancillary service provision using the experimentally obtained pressure-to-stress relation is used to normalize the results. This evaluation shows very clearly that the days during which the *La Bâtiaz* power plant is used for FCR and FRR ancillary services are more soliciting for the penstock, both at the top and the bottom. In fact, at the top of the penstock the fatigue wear rate is about 10x higher when these services are active, while for the bottom of the penstock, the provision of FCR and FRR yields a fatigue wear rate 5x higher than without ancillary service. Furthermore, these damage ratios are identical for the three pressure-to-stress relations, which shows that these results on the impact of ancillary services provision on penstock fatigue are not affected by the small discrepancies in the different ways of inferring the pressure-stress relationships listed in Table 2.

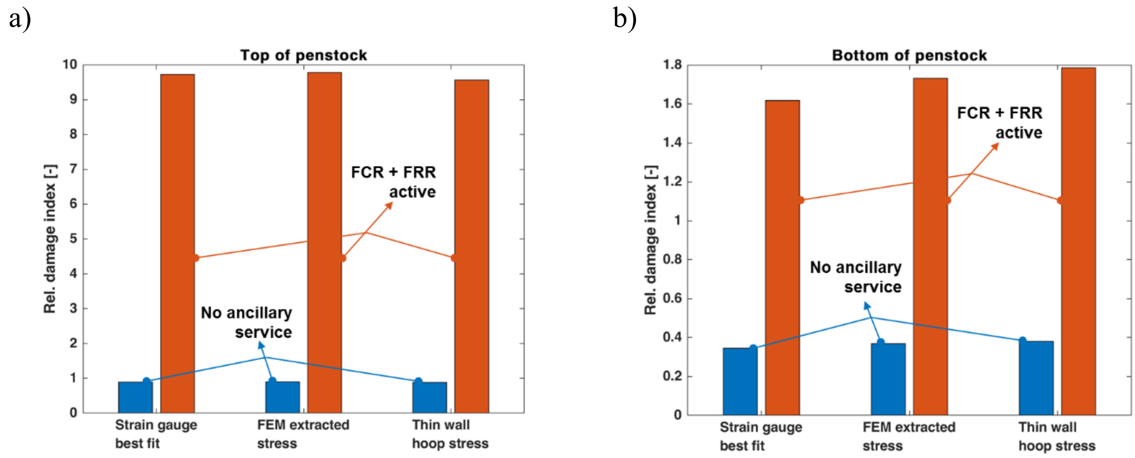

Figure 10. Comparison of the relative accumulated damage index along the penstock for 24h of operation with FCR & FRR ancillary services (orange) and without ancillary service (blue). The comparison is made for the different pressure-to-stress relations of

4. Conclusions

After demonstrating that the appropriate conversion of pressure to stress can be obtained through the analysis of FEM simulations or, for a straight section of an open-air penstock, the hoop stress equation for thin shells, the real-time transient pressures simulated by Hydro-Clone can be exploited to monitor the fatigue of the penstocks. By applying this approach to the case of *La Bâtiaz* high head Pelton turbine power plant, the considerable impact of ancillary services provision on penstock fatigue solicitation was highlighted. For the top of the penstock, the fatigue wear rate is about 10x higher when these services are active, while for the bottom of the penstock, the provision of FCR and FRR yields a fatigue wear rate 5x higher than without ancillary service.

By exploiting the data generated by Hydro-Clone, the health status and behavior of all essential system components can be checked at any time as well as non-measurable quantities. Such a digitalization system can be further used to optimize the parameters of the turbine governor in order to reduce the penstock steel lining fatigue and to find the best trade-off that fulfills the FCR and FRR ancillary services specification while improving the penstock lifetime, see for instance [14]. Another key advantage of this system is the identification of the penstock portion that is the most prone to fatigue. This information can be used to guide the experts during penstock inspections and thus focus on the most critical zones of interest. Finally, maneuvers that contribute significantly to fatigue, such as start/stop events, can be detected and optimized to reduce the penstock wear.

5. Acknowledgements

The present study was performed within the framework of the CTI project n° 28112.1 PFIW-IW "Penstock Fatigue Monitoring". The authors would like to thank *Innosuisse* - the Swiss Innovation Agency - for its financial support in this work.

References

[1] European Commission Energy Roadmap 2050, DG Energy, doi:10.2833/10759
[2] SwissGrid – Transmission System Operator, Transmission Code 2019, 2019

[3] Dreyer M, Nicolet C, Gaspoz A, Biner D, Rey-Mermet S, Saillen C & Boulicaut B 2019 Digital clone for penstock fatigue monitoring. *In IOP Conference Series: Earth and Environmental Science* (Vol. 405, No. 1, p. 012013). IOP Publishing

[4] Quaranta E, Bonjean M, Cuvato D, Nicolet C, Dreyer M, Gaspoz A, ... & Tomaselli G. 2020 Hydropower Case Study Collection: Innovative Low Head and Ecologically Improved Turbines, Hydropower in Existing Infrastructures, Hydropeaking Reduction, Digitalization and Governing Systems. *Sustainability*, 12(21), 8873.

[5] Nicolet C, Bollaert E, "Hydroelectric power plant real-time monitoring system and method", European patent EP 2 801 879 B1, 27.9.2017.

[6] Nicolet C, Bollaert E, "Hydroelectric power plant real-time monitoring system and method", European patent EP 3 285 128 B1, 18.11.2020.

[7] Nicolet C, Béguin A, Bollaert E, Boulicaut B and Gros G 2015 Real-time simulation monitoring system for hydro plant transient surveys *Int. Journal on Hydropower & Dams*, Volume **22**, Issue 5, pp. : 62-69.

[8] Nicolet C, Dreyer M, Beguin A, Bollaert E, Torrent S, Dayer J-D 2018 Hydraulic Transient Survey at Cleuson-Dixence with Real-Time Hydro-Clone Monitoring System, *Proc. of HYDRO 2018 Conference*, in Gdansk, Poland.

[9] Koutnik J, M Varner, V Linhart 2000 Service life determination of a 50 years old twin penstock PSPP Stechovice *Internationales Seminar Wasserkraftanlagen*,TU Wien.

[10] Hachem F. E., and Schleiss A. J. 2011 A review of wave celerity in frictionless and axisymmetrical steel-lined pressure tunnels *Journal of Fluids and Structures 27.2: 311-328.*

[11] Pachoud A. J. and Schleiss A. J. 2016 Stresses and displacements in steel-lined pressure tunnels and shafts in anisotropic rock under quasi-static internal water pressure *Rock Mechanics and Rock Engineering 49.4: 1263-1287.*

[12] E08 Committee. Practices for Cycle Counting in Fatigue Analysis, ASTM International;

[13] BS 7910 2013 Guide to methods for assessing the acceptability of flaws in metallic structures.

[14] Cassano S, Nicolet C and Sossan F, 2020, Reduction of Penstock Fatigue in a Medium-Head Hydropower Plant Providing Primary Frequency Control, *55th International Universities Power Engineering Conference (UPEC), Torino, Italy,* 2020, *IEEE*.