IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

Digital clone for penstock fatigue monitoring

To cite this article: M Dreyer *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **405** 012013

IOP Conf. Series: Earth and Environmental Science **405** (2019) 012013 doi:10.1088/1755-1315/405/1/012013

Digital clone for penstock fatigue monitoring

M Dreyer[1], C Nicolet[1], A Gaspoz[2], D Biner[2], S Rey-Mermet[2], C Saillen[3], B Boulicaut[3]

[1] Power Vision Engineering Sàrl, CH-1024 Ecublens, 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 Switzerland, most of the hydro power plants were installed between 1950 and 1970. These power plants play an important role for electrical power network stability through their operational flexibility and ability to provide ancillary services. These services lead to frequent start and stop sequences, as well as continuous power variations inducing transient pressures in the water conduits. Due to electricity market recent evolutions, existing hydropower plants are subject to new operating conditions and sequences which were not foreseen during the design phase. This significant increase of load variations enhances fatigue problems by soliciting the penstock faster than originally expected. While loading spectra are the fundamental input for any fatigue assessment procedure, they are often difficult, if not impossible, to quantify accurately. In this paper, we present how the implementation of a digital clone of the power plant, namely the Hydro-Clone real-time simulation monitoring system, can be used to fill this gap. By replicating the hydraulic transients of the powerplant, the digital clone enables real-time knowledge of the pressure variations throughout the water conduits. This feature is used to implement a fatigue module in Hydro-Clone by monitoring the penstock level of solicitation, based on the accumulated damage during its past and future operations. To validate this approach, stresses related to pressure variations are measured in situ by installing strain gages on the penstock of the 200 MW *La Bâtiaz* hydropower plant, owned by Electricité d'Emosson SA, and compared to the simulated values. Our results reveal the considerable impact of the supply of ancillary services on penstock fatigue wear.

1. Introduction

In the current context of energy transition, hydropower, which is the leading renewable source for electricity generation in the world, supplying 71% of all renewable electricity [1], is called upon to play a major role. Indeed, integration of large amounts of new renewable energies such as wind and solar power represents a challenging task as far as the power network stability is concerned. This intermittent pattern of new renewable energies needs substitution and storage capabilities that hydropower can offer thanks to various technical solutions that allow a high degree of adaptability and high-performance control capacities. Hydropower plants (HPP) play therefore an important role for electrical power network stability due to their operational flexibility and their ability to provide ancillary services, such as primary, secondary and tertiary control services. These services generate frequent start and stop sequences, as well as continuous power variations, inducing hydraulic transient phenomena in the water conduits. With the modernization of control systems, hydroelectric power plants, which are increasingly operated remotely, are responding more and more quickly. In addition, the installed capacity of hydropower plants is frequently augmented during rehabilitation, resulting in a higher discharge into the water conveyance system. As a consequence, most existing hydropower plants are subject to new operating conditions and sequences which were not foreseen during their design phase [2].

In Switzerland, most of the hydro power plants were built between 1950 and 1970, implying that their structural components are ageing. They were designed according to the maximal overpressure calculated as a static load of approximately 10 to 40% of the maximal static pressure, depending on the system layout and type of hydraulic machines [3]. The fatigue due to pressure oscillations was not taken into consideration. Given the catastrophic consequences that penstock rupture can have, such as the accident of the Cleuson-Dixence penstock in 2000 [4], it is crucial to properly monitor the fitness-for-service of these penstocks. However, the current state of research applied to hydroelectric plant wear focuses mainly on the fatigue of rotating parts, such as turbines, shafts and generators. In these components, the amplitude of stress variations is directly function of the mechanical torque and the number of cycles is related to the number of starts and stops. On the other hand, there are few solutions for penstock fatigue monitoring, as the determination of stresses due to transient pressure waves resulting from water hammer are less obvious than the mechanical stress due to a rotating torque. Without knowledge of the real loading spectra in the penstock, the best practice is to assume a certain frequency for each specific sequence likely to occur during the life of the HPP (start/stop, load rejections, etc.) and to assess the remaining lifetime of the pipes based on the contribution of each event [5][6].

In this context, the deployment of a digital clone of the power plant, namely the Hydro-Clone® real-time simulation monitoring system, can be used to fill this gap. By replicating the hydraulic transients of the powerplant, the Hydro-Clone system enables real-time knowledge of the transient pressures throughout the water conduits, which can be post-processed to derive the penstock level of solicitation. To validate this procedure, the stresses related to simulated transient pressures are compared to measured values in situ in the penstock of the 200 MW *La Bâtiaz* hydropower plant, owned by Electricité d'Emosson SA. This approach allows to assess the fatigue wear resulting from ancillary services by comparing the cumulative penstock damage for different operating modes of the hydropower plant.

2. Hydro-Clone Real-Time Simulation Monitoring System

The Hydro-Clone is an innovative Real-Time Simulation Monitoring System (RTSM) comprising a soundly calibrated and validated numerical copy of the hydropower plant able to reproduce in real-time any dynamic behavior of the installation based on boundary conditions measured in situ, i.e. a digital clone [7], [8]. This system, allows to continuously diagnose the health of a HPP by modelling all the major hydraulic and electrical components of the plant, using the SIMSEN software [9][10]. The Hydro-Clone general concept is illustrated in Figure 1. The system handles the tasks of real-time acquisition and transfer of the measured boundary conditions and quantities to the SIMSEN model, as well as data processing and diagnosis of the power plant health. A tailor-made database-storage system enables to display and analyze previous results. The analysis and comparison of simulated and measured quantities enable to understand at any time the fitness and behavior of all essential components of the system and to estimate non-measured/non-measurable quantities throughout the whole system [11]. The Hydro-Clone system has been implemented and tested since 2014 at the 200 MW *La Bâtiaz* power plant and has been operating continuously for 5 years.

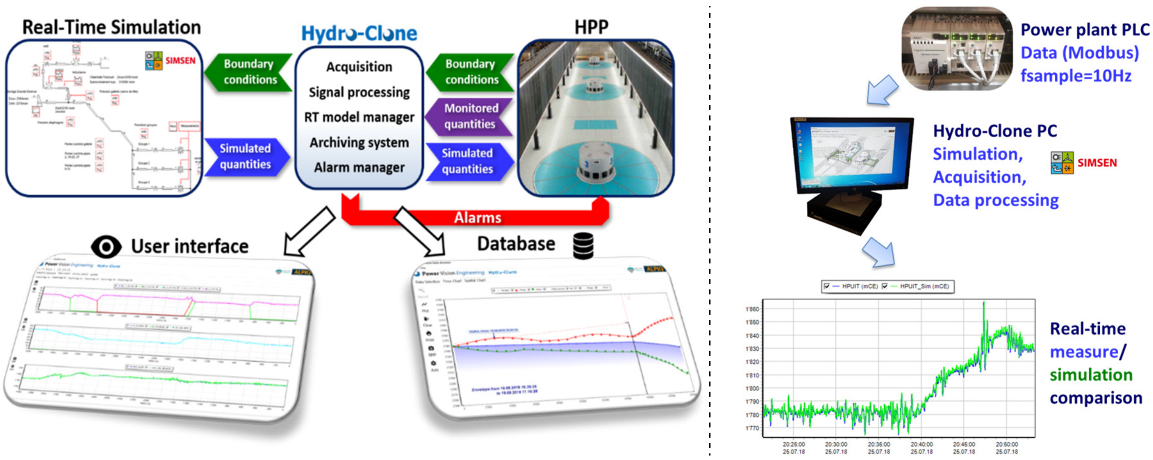

Figure 1. Hydro-Clone general concept with the illustration of the data exchange and visualization during real-time simulation (left), and its practical implementation with the HPP controller (right).

3. Presentation of *La Bâtiaz* power plant

The Electricité d'Emosson SA hydroelectric complex, which is jointly owned by ALPIQ and EDF, includes both the *Châtelard-Vallorcine* and the *La Bâtiaz* powerplants operated in cascade. The whole complex collects water from the Mont Blanc Massif, which is channeled into the Emosson Reservoir. With a maximum gross head of 659.5 mWC, the *La Bâtiaz* powerplant features two vertical Pelton units of 100 MW each, fed by an abduction system comprising an upper reservoir, a 9973 m long gallery of 3.5 m diameter, a surge tank with lower and higher expansion chambers, a 1253 m long inclined pressure shaft of 2.7 to 2.4 m diameter, and a manifold, see Figure 2. The SIMSEN model of this installation used in Hydro-Clone has been soundly validated with on-site tests, comprising an emergency shutdown of one unit operating at maximum power, cf. [8]. It should be mentioned that Electricité d'Emosson SA contributes to both primary and secondary control services.

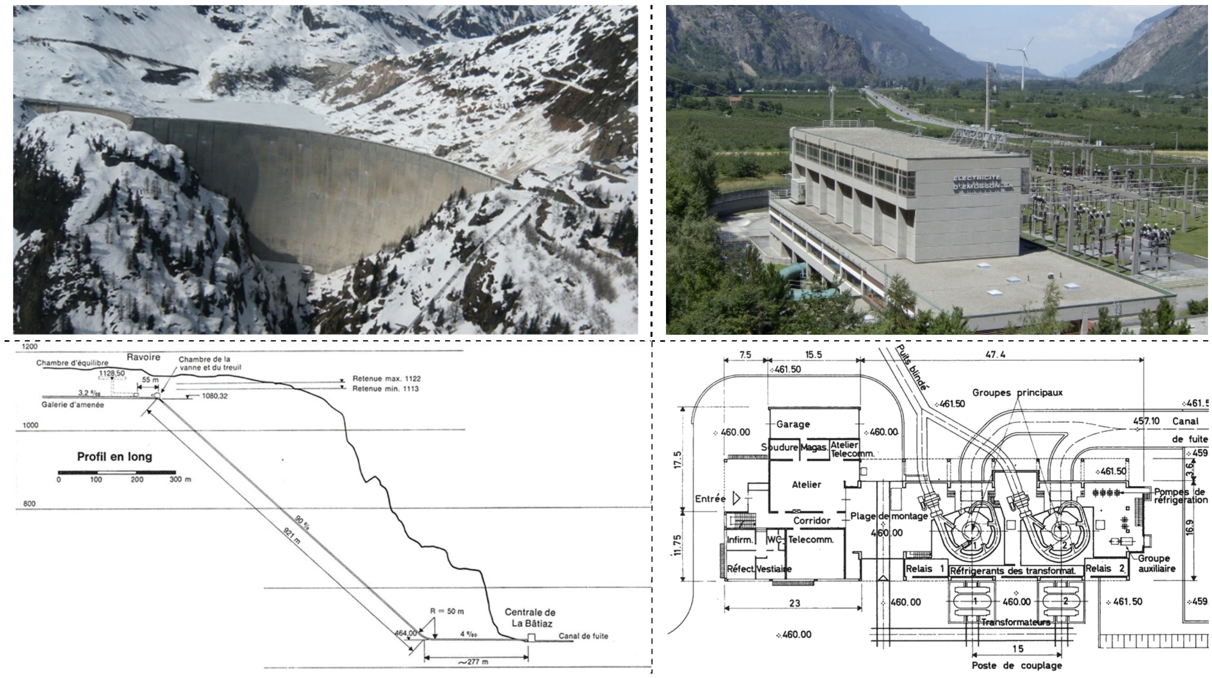

Figure 2. Top: photos of the Emosson dam and *La Bâtiaz* powerhouse. Bottom: layout of the 1.2 km penstock and top view of the 2x100 MW Pelton units with the manifold.

4. Methodology for penstock fatigue assessment

4.1.1. Stress assessment in penstock

Loading spectra are the fundamental input of any fatigue assessment procedure. It is therefore crucial to quantify accurately the stress fluctuations along the penstock, in order to assess the overall fitness of the pipes. However, they are often very challenging, if not impossible, to monitor on a permanent basis. The Hydro-Clone system can be used to overcome this difficulty. By replicating the hydraulic transients of the powerplant, Hydro-Clone makes it possible to know the pressure variations throughout the water conduits, which is a powerful tool for assessing the penstock fatigue, provided that the stresses can be correlated with these pressure variations. In principle, the relationship between the pipe internal pressure and stress at any point, $\Delta\sigma = f(\Delta p)$, could be determined using finite element modeling (FEM), taking into account the geometry and embedding conditions of each detail, as well as the eventual rock participation [12]. In the case of an open-air penstock, it is however fair to assume that the hoop stress equation for thin shells is valid, i.e.:

$$\Delta\sigma = \frac{\Delta p \cdot D}{2e} \quad (1)$$

IOP Conf. Series: Earth and Environmental Science **405** (2019) 012013 doi:10.1088/1755-1315/405/1/012013

in which D and e represent the pipe diameter and thickness, respectively. Using equation (1) the stress along the penstock can be evaluated using the pressures simulated by Hydro-Clone.

In order to test the validity of this assumption, the stress at the penstock bottom has been measured using *HBM RY81 6/350* rosette strain gages, mounted on a straight section of the pipe, in front of the Y-bifurcator of the manifold, see Figure 3. The acquisition was performed during a full day at a maximum sampling rate of 1 kHz. For practical reasons, the sampling rate of the pressure variations measured by Hydro-Clone is limited to 10 Hz for Pelton turbines. It is therefore important to verify that this low sampling rate does not eliminate any significant stress fluctuations. Figure 4 depicts the stresses obtained with the strain gages at two sampling rates during the normal stop of one unit: a "high" sampling rate of 1 kHz and a "low" sampling rate of 10 Hz, as would be generated by Hydro-Clone. As it can be observed, the 10 Hz sampling rate is sufficient to capture all major stress variations. The only additional fluctuations present at 1 kHz can be considered as white noise, the small amplitude of which does not contribute significantly to the fatigue. It should be noted that if this conclusion is certainly true in the case of *La Bâtiaz* power plant, which only features Pelton turbines, it may not be valid for HPP with Francis or pump turbines. In this case, high-frequency pressure fluctuations may have to be considered.

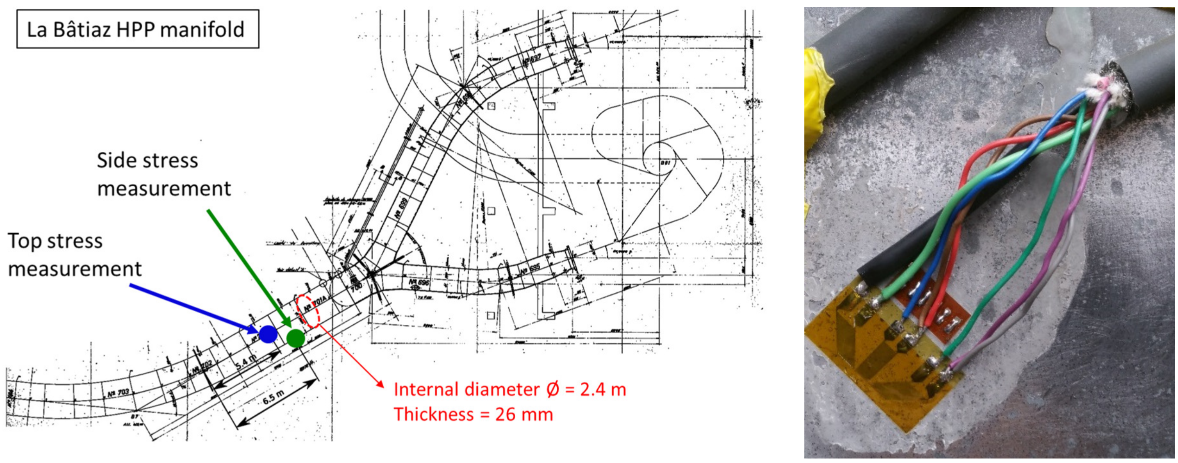

Figure 3. Left: sketch of the power plant manifold with the position of the strain gages. Right: photo of one of the strain gauge rosette, as installed on the penstock.

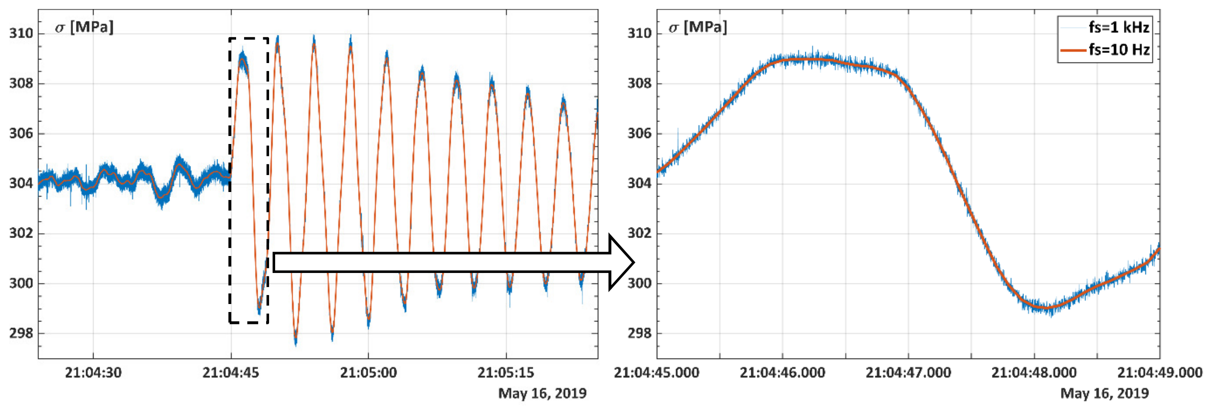

Figure 4. Comparison of the measured stress at the penstock bottom at a sampling rate of 1 kHz (blue line) and 10 Hz (orange line).

The comparison of the measured stress at the penstock bottom, obtained with the strain gages at a sampling rate of 10 Hz, and the value simulated by Hydro-Clone using equation (1) is illustrated in Figure 5. The agreement between the measured and simulated values is remarkable, since the maximum discrepancy between the two signals never exceeds 1%. In fact, the difference between measurement and simulation is less than 0.2% most of the time. This validates the previously described approach and demonstrates that the stress variations can be accurately inferred from transient pressures simulated by Hydro-Clone.

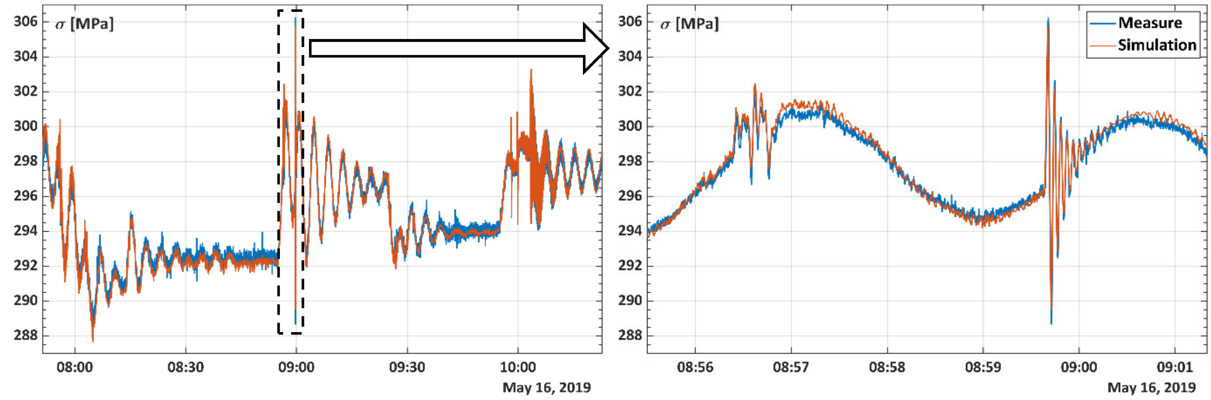

Figure 5. Comparison of the measured stress at the penstock bottom (blue line) with the simulated value computed by Hydro-Clone (orange line).

4.1.2. Penstock fatigue analysis

The global methodology of the penstock fatigue monitoring concept is illustrated in Figure 6. The Hydro-Clone system enables real-time knowledge of the transient pressures along a certain number of nodes in the penstock. These transient pressures are then converted into stress variation, using either equation (1) for open-air penstocks, or a more complex equation $\Delta\sigma = f(\Delta p)$ deduced from FEM for specific details where the hoop stress equation for thin shells is not valid. The number of fatigue cycles present in the stress-time history is determined by applying a rainflow cycle counting algorithm [13], following the ASTM standard [14]. Using Miner's rule, the cumulative damage for each penstock segment is then tallied with the appropriate S-N curve (also known as Wöhler's curve), in accordance with the BS7910 standard [15], yielding the damage index profile along the penstock.

The BS7910 standard [15] provides a set of normalized S-N curves, corresponding to different quality categories of the flaw, or detail, present in the structure. Since the parameters of the S-N curve are decisive for estimating the remaining lifetime of a structure, particular care must be taken in selecting the appropriate quality category. However, the scope of the present study is not to accurately determine the service life of the penstock, but rather to compare different HPP operating modes in terms of fatigue solicitation. For this reason, the choice of the S-N curve parameters is not crucial because the analysis is done in a relative way between the operating modes. In absence of precise knowledge of the potentially existing cracks and flaws, the choice is made to select the most conservative quality category, reported in Table 1. All other things being equal, the conclusions of this paper would not be altered by a different choice of parameters for the S-N curve. For this particular quality category, an effective fatigue limit of 11 MPa is suggested in the standard. By definition, all cycles with stress ranges equal to or below this fatigue limit can be neglected when performing a damage sum. Since there is no consensus on whether a fatigue limit applies for varying amplitude loading [16], the analysis is done both with and without the consideration of this cut-off limit.

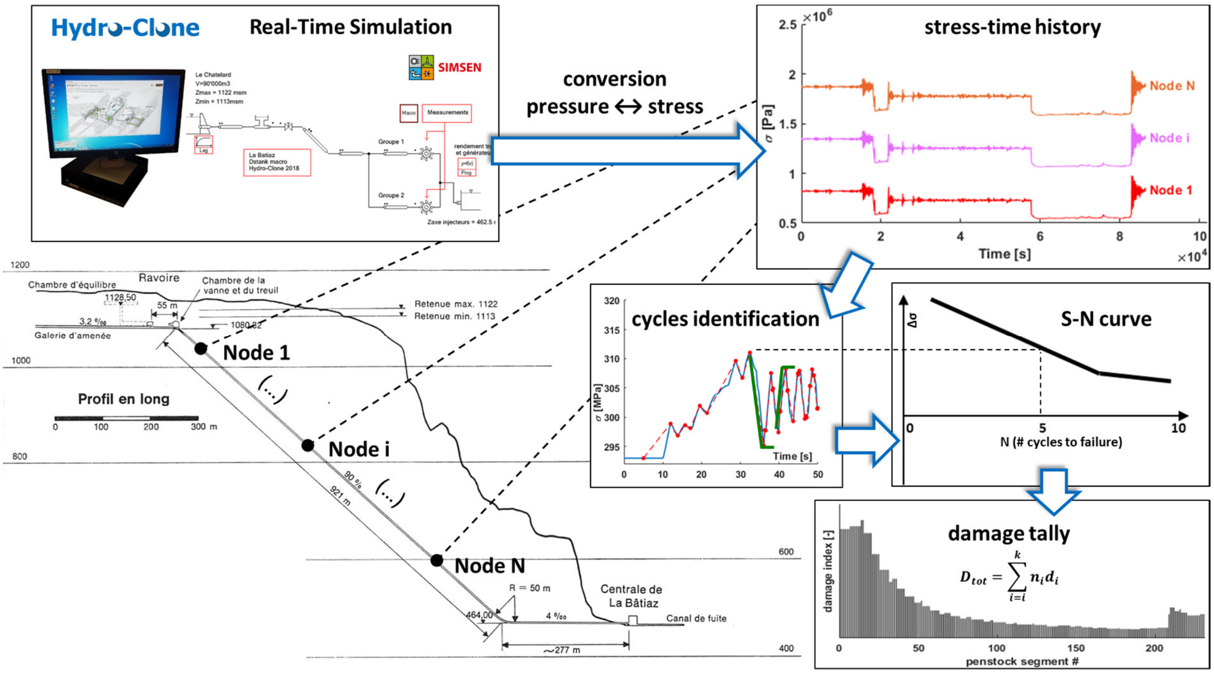

Figure 6. Global methodology of the penstock fatigue monitoring concept.

Table 1. S-N curve parameters

Quality Category	Constant in equation of curve $\Delta\sigma^3 N = constant$	Stress range, S, for 2×10^6 cycles	effective fatigue limit
Q10	2.38×10^{10}	23 MPa	11 MPa

4.1.3. Operating sequences for fatigue comparison

The previously described approach is used to assess the penstock level of solicitation during different typical operating modes of the power plant. To this end, four reference sequences, which are representative of a one-day operation with and without ancillary services, have been selected. A description of these four days, hereinafter refer to as *case A, B, C and D,* is given in Table 2. The temporal evolution of the power of each unit, with the resulting transient pressures at the penstock top and bottom is shown in Figure 7. *Cases A* and *B* correspond to the absence of ancillary service, without complete stopping of both units in the first case. *Case C* is representative of an operating day during which only secondary control service is provided, while *case D* reflects the supply of both primary and secondary control services.

Looking at the pressure signals in the right of Figure 7, it clearly appears that the amplitudes of the pressure variations are greater at the bottom of the penstock than at the top. However, since the nominal pressure as well as pipe thickness decrease with altitude, the relative stress variation can be significantly greater at the top of the penstock than at the bottom. In the *cases C* and *D*, the supply of ancillary service results in constant power setpoint variations, which in turn leads to transient pressures in the penstock. On the basis of these signals, it is not obvious to know the impact in terms of fatigue loading for each reference case, as each one features pressure variations of similar amplitude.

Table 2. Description of the four reference cases representative of different operating modes

Case	Description
A	24h without ancillary service, no simultaneous stopping of both units
B	24h without ancillary service, with two starts and stops of unit 2
C	24h with only secondary control service
D	24h with primary and secondary control services

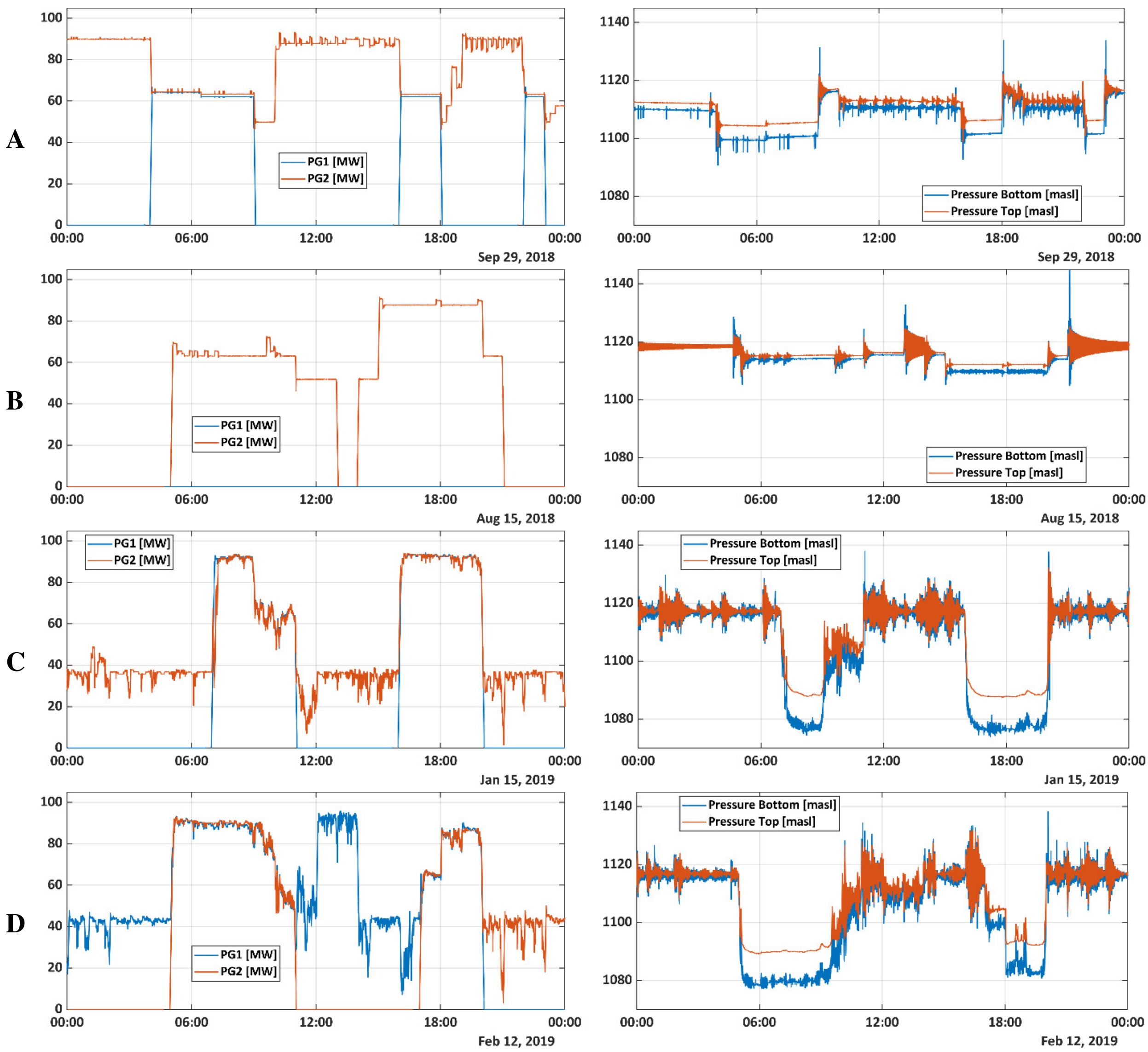

Figure 7. Temporal signals of the four reference days described in Table 2, with the power of each unit (left) and the corresponding pressure at the penstock top and bottom (right).

5. Results

Figure 8 and 9 show the accumulated damage index along the penstock for the *cases A, B, C, and D*, without and with the consideration of a fatigue limit in the damage tally, the rock contribution being neglected. In these figures, the top of the penstock corresponds to the origin of the x-axis, the turbines being located on the 1253 m abscissa. All results are presented in terms of relative damage index

IOP Conf. Series: Earth and Environmental Science **405** (2019) 012013 doi:10.1088/1755-1315/405/1/012013

compared to the reference *case A*, i.e. the maximum damage index along the penstock obtained for the *case A*, without considering a cut-off limit in the S-N curve, is used to normalize the results. This allows the fatigue loading of the different operating modes to be easily compared.

The results in Figure 8 clearly highlight the considerable impact of ancillary services provision on penstock fatigue solicitation. In fact, the supply of primary and secondary control leads to a damage index about 10 times more important than without ancillary service. In terms of service life, this results in penstock fatigue wear 10x faster when these services are active. The maximal damage index is obtained for the case with both primary and secondary control services. In order to isolate the impact of each service on the fatigue, the processing of a day with only primary control service would be needed. Such data, however, were not available for the *La Bâtiaz* HPP. The profile of the damage index shows that the upper part of the penstock, where the stress to pressure ratio is most important, is the most prone to fatigue. The consideration of a cut-off limit in the S-N curve does not change these findings. As shown in Figure 9, although the damage index is about 10% lower than the result in Figure 8, the ratio of 1 to 10 between cases with and without ancillary service is still evident.

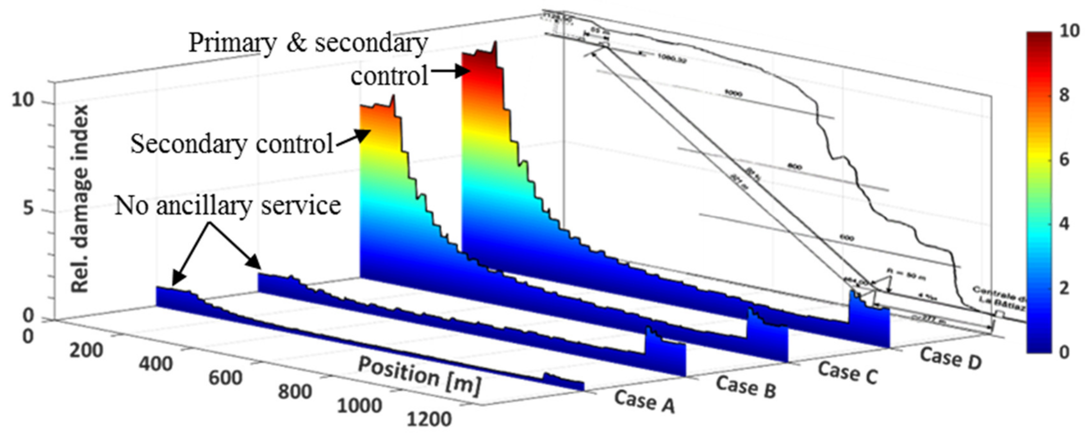

Figure 8. Comparison of the relative accumulated damage index along the penstock for 24h of operation under different modes (*Case A, B, C, D*, cf. Table 2). No cut-off limit in the S-N curve.

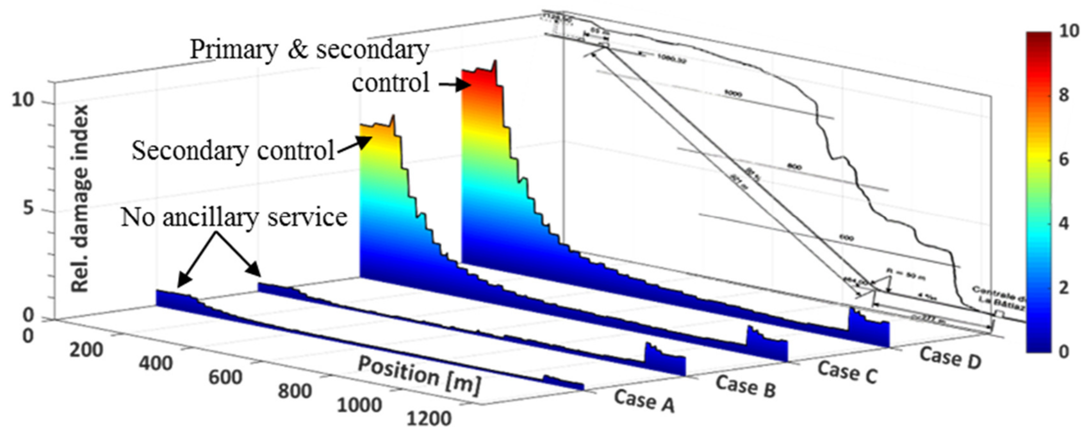

Figure 9. Same as Figure 8, but with a cut-off limit of 11 MPa for the amplitude of stress variations taken into account in the cumulative damage.

6. Conclusion

By taking advantage of the data generated by Hydro-Clone, in particular the real-time transient pressures throughout the water conduits, a fatigue analysis of the penstock of *La Bâtiaz* HPP was performed. After demonstrating that the transient pressures could be accurately correlated with stress variations, four typical operating days were compared to determine the impact of ancillary services on penstock fatigue. The results clearly highlight the considerable impact of the supply of primary and secondary control services on the penstock service life, with a dominant influence of the secondary control: the fatigue wear rate is about 10x higher when these services are active.

7. 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] World Energy Council, 2016 "World Energy resources, Hydropower 2016".

[2] Nicolet C, Berthod R, Ruchonnet N, Avellan F. 2010 Evaluation of possible penstock fatigue resulting from secondary control for the grid. *Proceedings of HYDRO*.

[3] C.E.C.T. 1980 Recommendations for the design, manufacture and erection of steel penstocks of welded construction for hydroelectric installations. *European Committee of Boiler, Vessel and Pipe Work Manufacturers*.

[4] Marietta P, Détraz H, Berthod R, Nicod J-F 2009 Rehabilitation of the Cleuson-Dixence High Pressure Shaft, *HYDRO 2009 Conference and Exhibition,* Lyon.

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

[6] Duparchy F, Chambas PA, Marin H, Pereira F and Combaz T 2013 Impact of pressure fluctuation on the fatigue life of high pressure penstocks. *Proceedings of the Conference on High Strength Steels for Hydropower Plants,* Graz University of Technology.

[7] Han M, Beguin A, Nicolet C and Kawkabani B 2014 Advanced Condition Monitoring System for Synchronous Machines Based on Real-Time Simulation *Proceedings of the XXIth International Conference on Electrical Machines*, Berlin, Germany, pp.: 1479-1485.

[8] 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.

[9] Nicolet C 2007Hydroacoustic modelling and numerical simulation of unsteady operation of hydroelectric systems *EPFL, Thesis n° 3751*.

[10] Nicolet C, Greiveldinger B, Hérou J-J, Kawkabani B, Allenbach P, Simond J-J and Avellan F 2007 High Order Modeling of Hydraulic Power Plant in Islanded Power Network *IEEE Transactions on Power Systems* 22 1870-1881

[11] 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.

[12] Pachoud AJ, Berthod R, Manso P, Schleiss A 2018 Advanced models for stress evaluation and safety assessment in steel-lined pressure tunnels. *Hydropower & Dams*; 25(5):77-82.

[13] Niesłony A. Determination of fragments of multiaxial service loading strongly influencing the fatigue of machine components 2009. *Mechanical Systems and Signal Processing*, 23(8):2712-21.

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

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

[16] Nussbaumer A, Borges L, Davaine L 2012 Fatigue Design of Steel and Composite Structures: Eurocode 3: Design of Steel Structures, Part 1-9 Fatigue, John Wiley & Sons;