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To cite this article: Jean Héraud *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **240** 052034

Empirical findings on the transmission of draft tube instabilities along the penstocks of hydraulic plants

Jean Héraud[1]; Bruno Lecomte[2]; Mathieu Comelli[3]; Pierre-Yves Lowys[4] and Goran Pavic[5]

[1] Hydromechanics Engineer, EDF DTG MPSH, 21 Av. Europe, 38040 Grenoble, France
[2] Senior Engineer, EDF DTG MPSH, 21 Av. Europe, 38040 Grenoble, France
[3] Hydromechanics Engineer, GE Renewable Energy Hydro Solutions, Hydromechanics COE, 82, Avenue Léon Blum, BP 75, 38041 Grenoble, France
[4] Senior Consulting Engineer, Dynamic Systems, GE Renewable Energy Hydro Solutions, 82, Avenue Léon Blum, BP 75, 38041 Grenoble, France
[5] Professor Emeritus, LVA, INSA de Lyon, 69621 Villeurbanne, France

Abstract. On EDF hydraulic production plants equipped with Francis turbines, there have been related some cases of significant pressure fluctuations detected in the upper parts of the penstock when units were operating in the high load pressure surge zone. There was no decrease of the Peak-to-Peak pressure fluctuations along the penstock in the upstream part as it could be expected. To understand the phenomenon, on site tests have been carried out using innovative non-intrusive dynamic pressure sensors in many points along the penstock allowing the analysis of upward and downward waves and their "interferences". These interferences cause in some cases standing waves for which the envelope of pressure oscillations along the penstock exhibits nodes and anti-nodes whose positions are relatively fixed along the penstock for a given operating point of the turbine. It appears that the ratio [Frequency of surge]/[Natural frequency of the penstock] conditions directly the number of nodes. This point is important because upper zones of the penstock close to the surge tank have generally not been designed to withstand high values of pressure fluctuations. For high number of ratio (3, 5, 7…), long term operation may induce mechanical fatigue of the penstock. A statistical approach was performed based on the dynamic signal databases of EDF and GE comprising data analysis of 21 occurrences of strong axial pressure surges of high load. It seems that certain values of the frequency ratio favour this resonance. This emphasizes the role of water exchanges between the rope and the penstock (complementarily with the draft tube) in establishing the conditions of resonance.

1. Introduction

Pressure surges are sometimes encountered in Francis turbines, and interpreted as axial hydraulic instabilities involving the resonance of the system composed of the draft tube rope, the turbine, and the penstock. This phenomenon happens at high load but can also be observed at part and low load. Such resonance may result in unacceptable pressure pulsation and electrical power swing (Tadel, 1986 [11]).

At part load, both forced and self-excited oscillations can occur. The classical case of system resonance under forced oscillation involves the draft tube helical vortex rope which generally imposes its own precession frequency, and has been widely explored theoretically and experimentally since long time (Couston, 1998 [2]). Methodologies have been proposed to simulate the system behavior (Nicolet, 2006 [9]), and to predict the cavitating volume properties and the system response using a combination of reduced scale model testing and 1D/3D numerical simulations (Alligné, 2011 [1]) (Landry, 2016 [8]). Recent works have also demonstrated the possibility to derive the vortex and the system frequencies from the single swirl number (Favrel, 2017 [5]). However, in an industrial context and given the high sensitivity of the key parameters (wave speed, rope compliance…) to the operation conditions, these processes are still challenging. In order to improve their capacity of prediction, further research is still ongoing in order to better avoid the risk of part load resonance on a prototype machine. The specific case of upper part load self-excited vortex rope is also complex to predict, but can usually be mitigated by efficient countermeasures.

At full load, self-sustained pressure surge is sometimes observed on Francis or reversible pump-turbines. In some cases, this leads to significant pressure and power swing, and can even jeopardize the capacity of the turbine to operate at its maximum output. The physical mechanism has been discussed in the past years and researches pointed out the destabilizing influence of the mass flow gain factor (Koutnik, 1996 [6]), as well as the non-linear dependence of the cavitation compliance to the Thoma number to initiate the surge (Koutnik, 2006 [7]).

Although most of above mentioned works focused on the comprehension of the phenomena occurring in the draft tube in order to characterize the mechanisms and the governing parameters of the self-excited pressure surge, this paper focuses on the coupled response of the penstock with the excitation. It develops an original approach based on experimental observations. For the first time, a large number of surge events measured on various hydro-plants by EDF and GE Hydro have been gathered in a single database, allowing empirical analysis and interpretation of the phenomenon. The paper will mostly consider the cases of full-load surge for which many measurements were available, but the interpretation should still be valid for less frequent low-load pressure surges (occurring at a discharge lower than in the helical part load rope area).

The specificity of these experimental cases is that the pressure pulsations are not decreasing along the penstock as in the case of most load rejections. On some EDF Francis turbines, cases of significant pressure fluctuations have even been detected in the most upper part of the penstock when the units are operating in the full-load surge zone. Such dynamic loadings are usually not considered in the design of the penstock and in some rare cases, they can exceed the fatigue strength of the material. An original non-intrusive method for mapping the dynamic pressure on several points distributed along the penstock has been developed and enables to illustrate the establishment of standing waves.

2. Terminology

- **Frequency of Penstock : $F_{Penstock}$:** The first ¼ wave hydro-acoustic eigenfrequency of the penstock filled with water (corresponding to open-closed boundary conditions at both ends):

$$F_{Penstock} = \frac{a}{4L}$$

- a Average acoustic wave velocity in the water of the penstock.
- L Length between the turbine and the upper location of wave reflection

This frequency can be either:

- Calculated theoretically from the estimated length and the calculated wave velocity
- Or determined experimentally after a load rejection or a shutdown of the turbine (frequency of free pressure oscillations after complete closure of the wicket gate) ($F_{Penstock\ Load\ rejection}$)

- Or measured during instabilities ($F_{Penstock\ Instability}$)

- **Frequency of axial Pressure Surges: F_{Surge}** : The frequency of the pressure pulsations measured in resonant conditions
- The "**Penstock Wavenumber**" (PW) is then defined as:

$$PW = \frac{F_{Surge}}{F_{Penstock}}$$

This "Wavenumber" is a little different from the standard physical definition where it represents a number of oscillations per unit of length. In fact the above definition conditions the number of standing waves along the whole penstock initiated by the pressure surge. More precisely, it is the numbers of quarters of waves.

- The "**Rope-Penstock Resonance Factor**" (RPRF) is defined as:

$$RPRF = PW - 2k$$

where k is a positive integer number, and RPRF ∈ [0-2[. In terms of Euclidian division, RPRF is equal to the remainder of PW modulo 2. For example: If PW = 4.7, then RPRF = 4.7 – 4 = 0.7 and k=2

3. Non-intrusive dynamic pressure measurement along the penstock via PVDF wires

3.1. PVDF wires

"PolyVinyliDene Fluoride" (PVDF), polymer with piezoelectric properties, is available in many forms and for various uses. We use it here as a string gauge in the form of a wire.

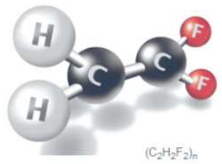


Figure 1. PolyVinyliDene Fluoride polymer.

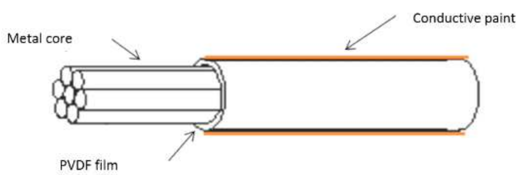


Figure 2. PVDF wire diagram.

Submitted to variations of traction, the wire generates electrical charge proportional to its elongation. We use this property by winding the wire around a pipe subjected to pressure variations. For the low frequencies of surges encountered in hydraulic plants (with plane pressure waves), we can admit proportionality between variations of pressure in the pipe and elongation of the wire.

The major benefit is then to be able to measure the pressure variations in any section of pipe, without drilling it as in the case of a traditional intrusive sensor.

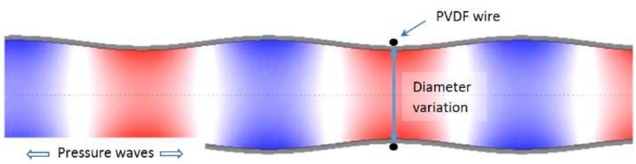


Figure 3. Schematic diagram of using PVDF wire on a pipe.

Knowing the characteristics of the pipe (diameter, thickness and properties of metal) and the sensitivity of the wire, we can deduce the pressure variations in the pipe from the electrical measurements of wire charge:

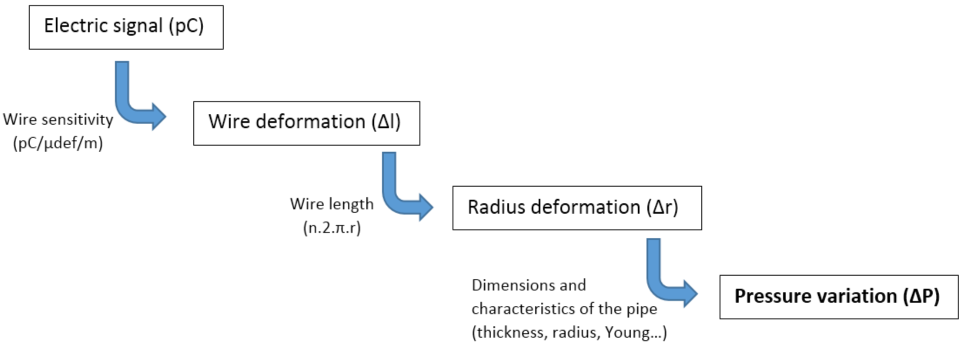


Figure 4. Pressure variation calculation.

3.2. Implementation on penstocks

This method is simple to implement, provided that the periphery of the penstock is accessible. After tracing and rough cleaning of the measuring section, one or more windings of the wire are positioned by applying a manual preload. Final fixing is done with a cable clamp. The number of windings is chosen depending on the diameter, the thickness and the estimated amplitude of the pressure variations, so as to produce an optimal electrical signal. The wire is connected to a charge amplifier, whose voltage or current signal is recorded on a digital datalogger.

Figure 5. Mounting example - 1 turn on 1 m diameter pipe - wire and amplifier.

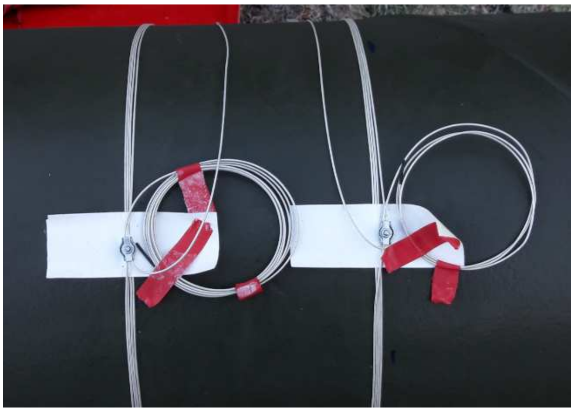


Figure 6. Mounting example - 4 turns on 0.45 m diameter pipe.

3.3. Validation and limits of use of the PVDF wire measurement

The wire method has been validated during measurements realized on several EDF plants (collaboration of EDF, Insa Lyon, Matelys Research and GE Hydro France). (Pavic, 2017 [10] gives elements of validation for this type of measurement).

With the amplifiers currently used (B&K 2635) experience shows that measurements are feasible as long as the pressure variations (either oscillations or transient) are sufficiently fast (oscillation frequencies higher than ~1 Hz For stationary regimes, or pressure variations lower than ~1 s for transient conditions).

Any measurement of the static value of the pressure is therefore excluded. In addition, a low frequency drift may occur in the signal, but is easily removed by high pass filtering at 0.5 Hz.

4. Experimental results: 2017 test in Monceaux-la-Virole plant (France)

4.1. Presentation of the measurements

The plant is composed of 2 vertical Francis turbines (7.5 MW each) under 150 m head without air admission in turbines. Both units are connected to a single penstock (1.8 to 2 m Ø and 490 m long).

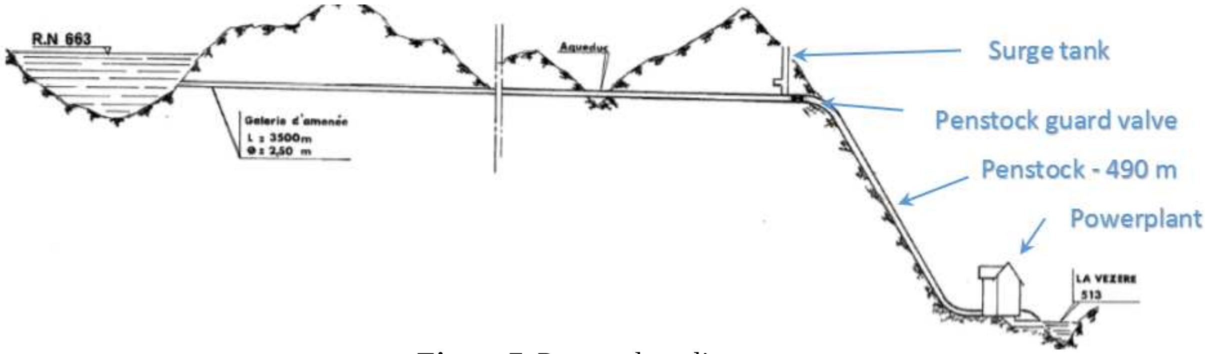


Figure 7. Power plant diagram.

Severe high load surges have been recorded on the 2 units. The objective of the measurements carried out by EDF in collaboration with GE was to characterize the propagation mode of the pressure waves in the penstock, when the turbine is in this unstable regime.

The following sensors were connected to a common datalogger:

- 3 classic sensors (Draft tube, Spiral case and Penstock guard valve)
- 8 PVDF wires regularly spaced along the penstock

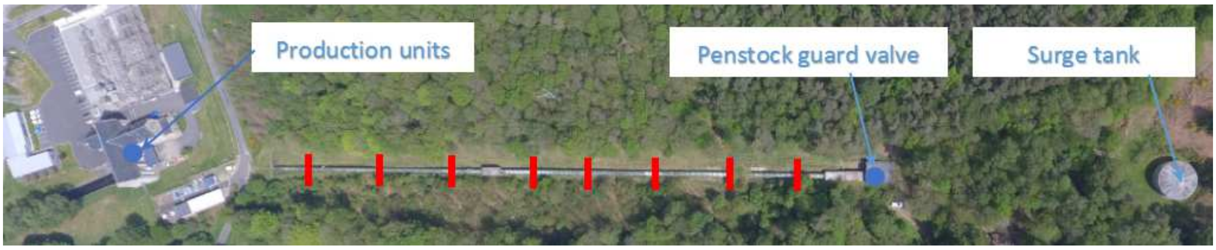
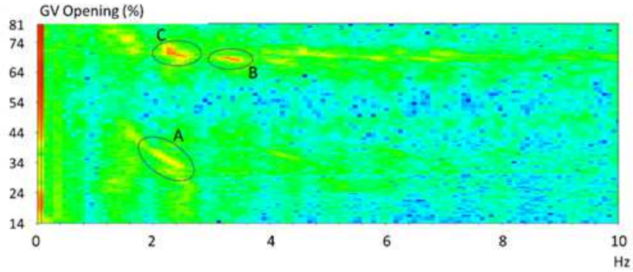


Figure 8. Pressure measurement scheme - classical sensors (blue) and PVDF wires (red).

4.2. Results

The entire range of output of the unit has been explored, allowing to identify various pressure fluctuation zones:



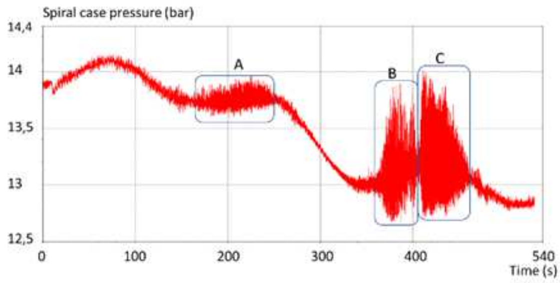


Figure 9. Cascade spectrum of spiral case pressure. **Figure 10.** Spiral case pressure low-pass.

Three main pressure fluctuation zones are identified of the spiral case pressure when the discharge increases:

- Part load pulsation zone A of relatively low amplitude at 2.1 Hz (not studied in this paper)
- High load pressure pulsation zone B at 3.4 Hz
- High load pressure pulsation zone C at 2.35 Hz

The two high load surges are very close in term of discharge, and only a minor change in guide-vane opening makes the frequency switch from one to another in few periods of the pressure oscillations.

The signals have been band-pass filtered [0.5 - 50 Hz] to focus on the low frequency surge phenomenon.

4.2.1. 3.4 Hz pressure surge (zone B)

The pressure fluctuations in the draft tube and in the spiral case are in phase, with a higher amplitude inside the spiral case (Figure 11). In addition, the signals between the spiral case and the penstock guard valve are out of phase, with similar amplitudes. (Figure 12).

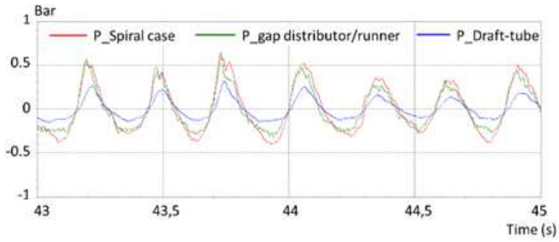


Figure 11. In-phase pressure signals.

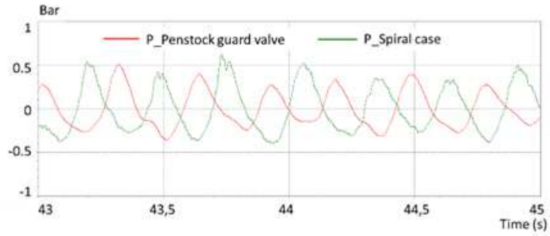


Figure 12. Out of phase pressure signals.

To explain this wave propagation along the penstock we look at the pressure fluctuations measured by the PVDF wires distributed along the penstock. The signals are either in phase or out of phase, showing the appearance of a standing wave.

On the following temporal diagram, we can see the oscillations of 11 points of pressure measurement. The vertical spacing of the signals ordinates has been made proportional to the positions of the measuring points along the penstock.

The peaks of the upward waves and corresponding hollows of the reflected waves are clearly visible. We also see the rise of the pressure troughs and their descent reflected in the form of pressure domes.

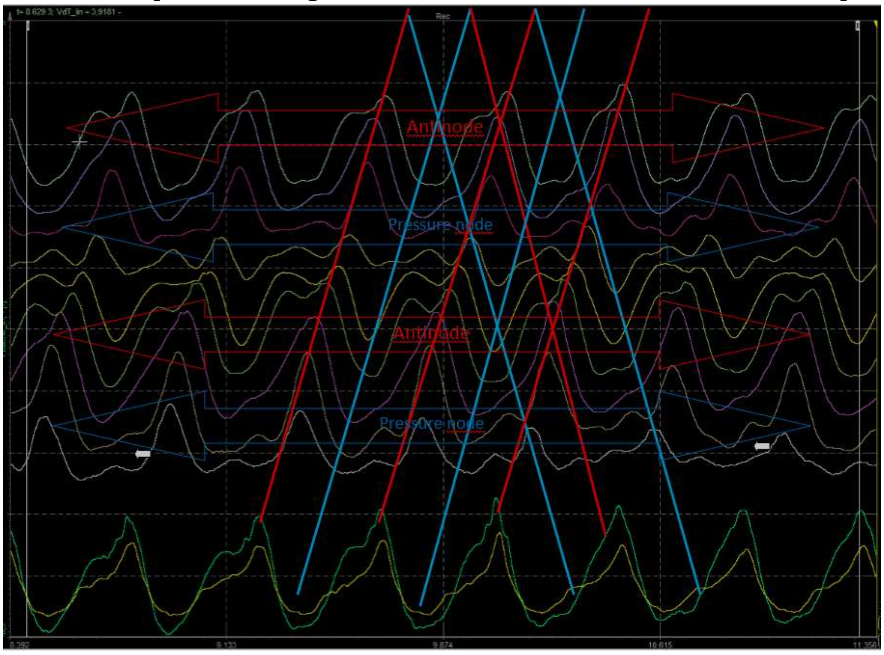


Figure 13. Visualisation of upwards and downwards waves.

We can see, by looking carefully, how these upward and downward waves transiting along the linear of the penstock add up algebraically to create nodes and antinodes.

A Fast Fourier Transform (FFT) is applied on each signal to extract its amplitude and phase at the surge frequency of 3.4 Hz. Then every pressure fluctuation measurement is set at its position along the penstock to reconstruct the resulting standing wave:

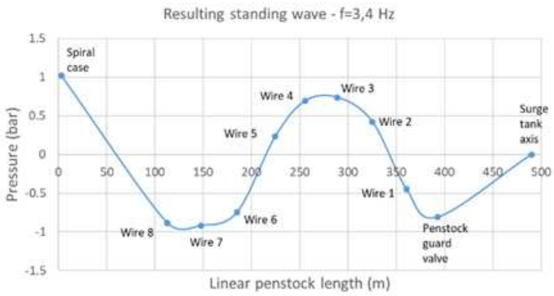


Figure 14. Snapshot of the 3.4 Hz pressure pulsation in the penstock.

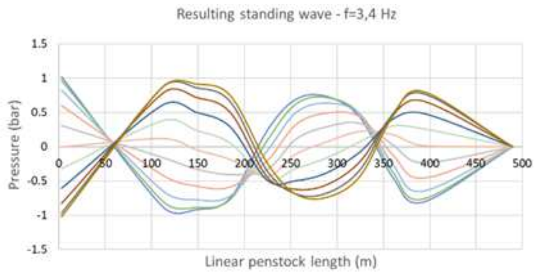


Figure 15. Nodes and anti-nodes in the penstock. The 7/4 wave form is clearly shown.

The measured pressure pattern indicates a resonance of the system Rope-Adduction. Nodes and antinodes are clearly exhibited, showing points of high penstock oscillations, even at the upper parts of the penstock. The resulting wave has an approximately 7/4 wave shape (~seven ¼ of wave).

4.2.2. 2.35 Hz surge (zone C)

The pressure fluctuation along the penstock at 2.35 Hz were analysed in a similar manner to get the resulting standing wave. For this surge, the pressure fluctuations at the spiral case and at the penstock guard valve are in phase:

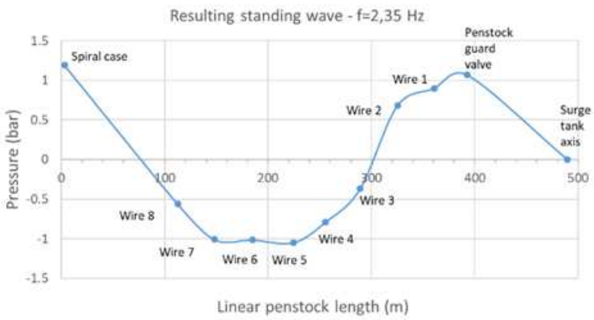


Figure 16. Snapshot of the 2.35 Hz pressure pulsation in the penstock.

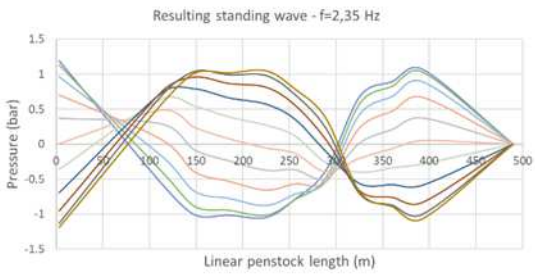


Figure 17. Nodes and anti-nodes in the penstock. The 5/4 wave form is clearly shown.

The resulting wave has an approximately 5/4 wave shape (~five ¼ of wave).

4.3. Evaluation of wavenumbers

There is a resonance of the system including the rope and the penstock.

The hydro-acoustic eigenfrequency of the penstock between the turbine and the surge tank is determined during transient event after load rejection of the turbine: 4L/a = 1.92 s (FPenstock Load rejection = 0.52 Hz).

	3.4 Hz surge	2.35 Hz surge
Penstock Wavenumber (PW)	6.54	4.52
Rope-Penstock Resonance Factor (RPRF)	0.54 (k=3)	0.52 (k=2)

4.4. Interpretation

View from the penstock, the rope can be interpreted as a periodic generator of water hammers during the surges. If the period of surge is sufficiently small compared to the time of a round-trip wave in the penstock (2L/a) (i.e. PW> 2), the rising pressure wave of the water hammer "n" crosses the downward pressure wave of the water hammer "n-1" (even "n-2", "n-3" ...) reflected at the surge tank.

The reflected rising and descending waves add up algebraically. These interferences cause the envelope of pressure oscillations along the penstock to draw nodes and antinodes whose positions are relatively fixed along the penstock if the surge is periodic.

For odd values of PW (1, 3, 5,...), the spiral case corresponds to a pressure antinode of the oscillation, and pressure node for even values of PW (2, 4, 6 ...).

The higher the Penstock Wavenumber is, the upper the last upstream antinode of pressure fluctuations is located in the penstock.

5. Proposition of a criterium for instability transmission along the penstock

The following criterium is proposed to anticipate the position of the uppermost antinode in the penstock:

Penstock wavenumber	Upper point of the penstock reached by an antinode of pressures (in % of the length of the penstock counted from the turbine)
PW>1 (less than half of the surges)	$[\mathbf{1}-\frac{F_{Penstock}}{F_{Surge}}]$ (%)
PW<= 1 (more than half of the surges)	0% (maximum in the spiral case)

Examples:

Figure 18. If PW = 3 (3/4 of wave): the upper point of maximum fluctuation = 1-1/3 =66% of linear of penstock.

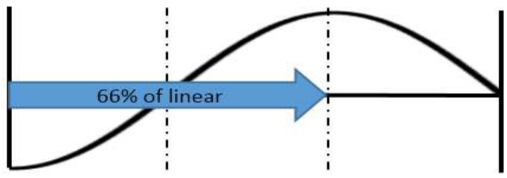
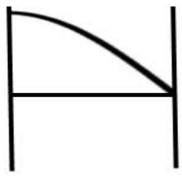


Figure 19. If PW = 1 (1/4 of wave): Maximum pressure fluctuation is in spiral case.



6. Statistical approach for the Rope-Penstock Resonance Factor

6.1. Results with frequency of penstock measured after load rejection

The below statistic presents 21 accentuated full-load surges measured by EDF or GE Hydro France on Francis turbines.

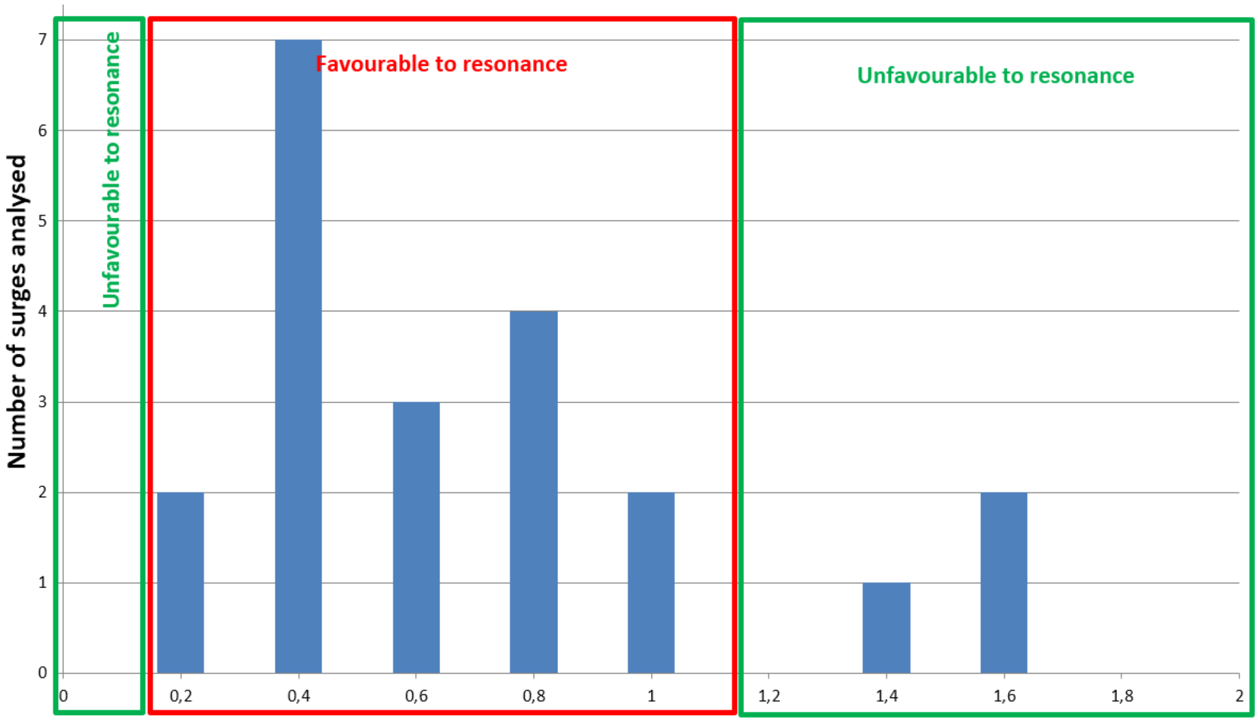


Figure 20. Rope-Penstock Resonance Factor (RPRF) (calculated with $F_{Penstock\ Load\ rejection}$) (abscissa value of 0.4 in the diagram means interval [0.4-0.6]).

As we can see, there is a statistical tendency to have more surges for RPRF Є [0.2-1.2] (18 surges, or 85 % of the listed events), than in intervals [0.0-0.2] & [1.2-2.0[(3 surges). Many surges have a RPRF value in the interval [0.4-1.0].

6.2. Physical Interpretation and discussion

It seems that only certain values of Penstock Wavenumber (PW) and RPRF favour this resonance (the penstock must supply water (in addition to the draft tube) when the rope collapses and not when it grows). These favourable values of PW are the intervals: [0-1] or [2-3] or [4-5]… (but not [1-2] nor [3-4] ...). Consequently, RPRF is in interval [0-1].

The diagrams in the table below represent examples of instant "snapshots" of the fluctuating pressure and discharge in the system:

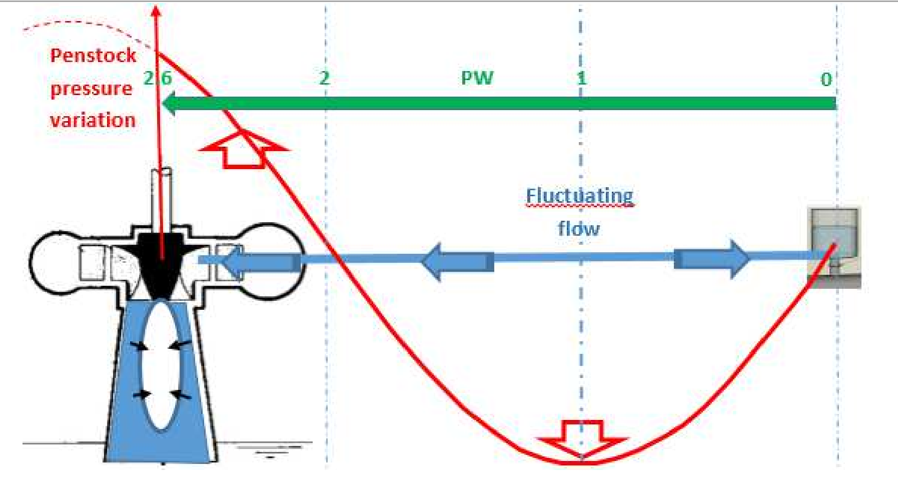
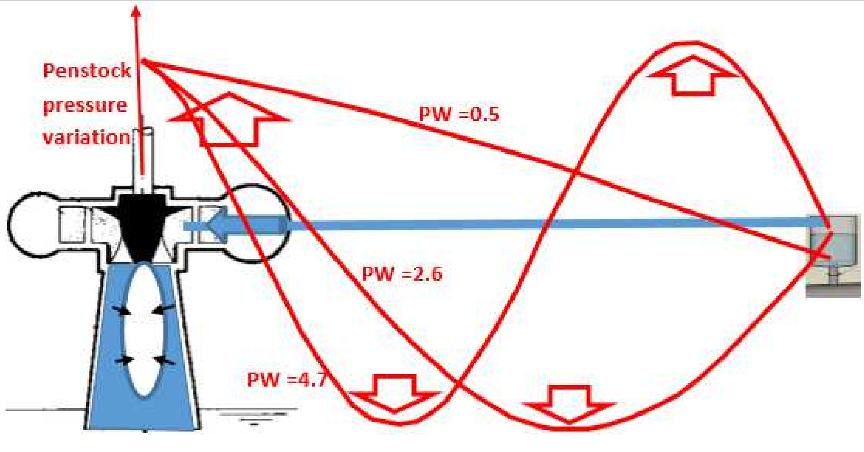
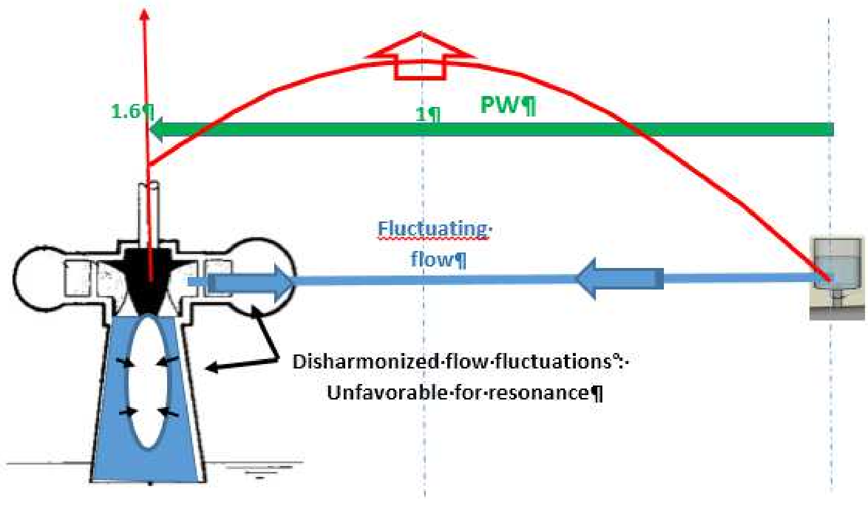
 	Configuration favourable to resonance (PW=2.6 & RPRF=0.6). When the pressure increases in Spiral Case & Draft Tube: • The volume of the rope decreases and therefore it absorbs a volume of water • The spiral case supplies this volume of water
 	Other frequencies of surge can realize this favourable matching PW =0.5 or 2.6 or 4.7 for example. RPRF ϵ [0-1].
 	But not all frequencies favor the resonance: PW =1.6 for example. RPRF = 1.6

Figure 21. Exchanges of fluctuating pressure and discharge along the penstock.

The experience of many surge measurements showed that draft tube and spiral case pressure signals are in phase (or almost in phase). Pressures and flows fluctuations along the penstock are offset by 90°.

At the pressure nodes, flow fluctuations are maximum and pressure fluctuations are minimum (Vice versa, at the antinodes).

Thus the frequency of surge could be partly conditioned by the Penstock Wavenumber (PW) that ensures harmonized water exchange between rope and penstock, and consequently influenced by the characteristics of the penstock. This could explain the difficulty of transposition of high load surges from model to prototype, if the properties of the intake hydraulic system are not taken into account.

Moreover, in the high load surge zone, a progressive increase of the load can be interpreted as:

- A progressive increase of the average volume of the rope
- An increase of the water volume exchanged at each oscillation (for a given peak-to-peak fluctuation of draft tube pressure).
- A decrease of the surge frequency (and consequently of the Penstock Wavenumber) to adjust to this increase of water volume:
  - Continuously within a favourable range of PW. Example: PW interval [6-7] (This way, the spiral case is getting closer to a node of pressure)
  - In some cases, by sudden switch to avoid an unfavourable zone (RPRF€]1-2]). For example: PW switches from 6 to 5. The volume of water exchanged with the penstock (all things equal otherwise) is proportional to the temporal integration of spiral case pressure on a half period of the surge). The slower the surge, the more important the volume of water is exchanged)

These observations and interpretations do obviously not allow to predict, for a new project, the adapted lengths of pipes in order to avoid high load surges. However, it allows to identify, for a given project, ranges of possible high load surge frequencies. The effective emergence of these surges is probably related to the conditions in the draft tube (compliance of rope …)

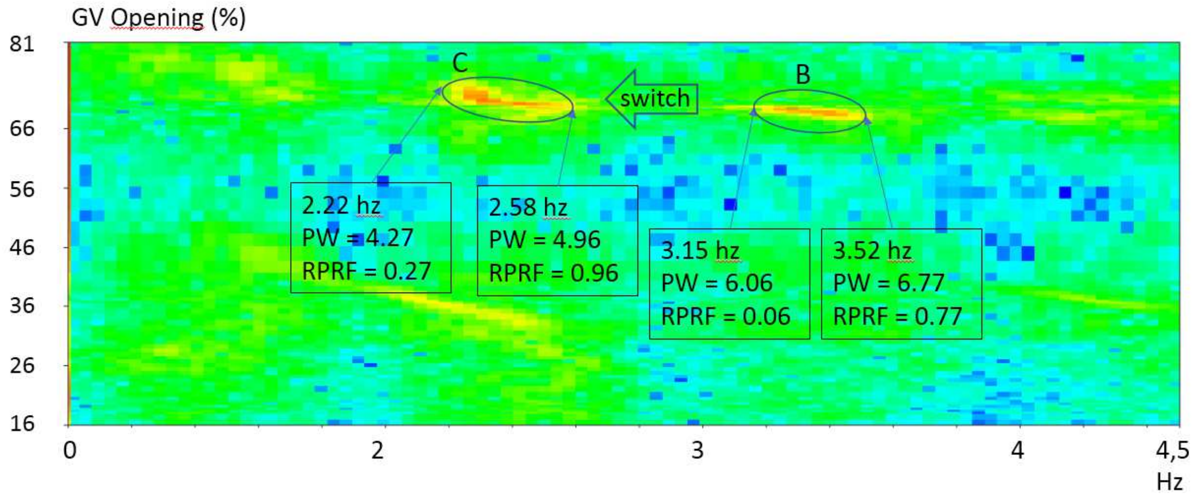


Figure 22. Cascade spectrum of spiral case pressure sensor with identification of PW.

7. Consideration about the location of the wave reflection

In this paper, the presented values of Rope-Penstock Resonance Factor (RPFP) have been calculated with $F_{Penstock\ Load\ rejection}$, because this frequency is easy to measure with nearly no subjectivity.

Nevertheless, the best frequency for calculation would certainly be FPenstock Instability (estimated via the time of wave roundtrip in the penstock during the surge).

$F_{Penstock\ Instability}$ evaluation is sometimes possible by interpretation of draft tube temporal pressure fluctuations (with the help of spiral case signal too). But often, it is not possible or too subjective. A better interpretation is permitted by mathematical separation of upgoing and downgoing waves from 3 sections of pressure measurements spaced from 20 to 30 meters [Pavic, 2017].

Both frequencies are in most cases identical. Nevertheless, according to EDF measurement experience (based on field measurement and permanent monitoring of 300 penstocks), there are some cases where they differ due to the location of the upper point of wave reflection. During load rejection, the point of reflection is generally the free surface at the top of the surge tank (or the outlet of the penstock in the upstream reservoir). Moreover, the conditions of reflection in the turbine are not known precisely and seem variable from one case to another.

During full-load surges, reflection may sometimes occur completely or partially in some other places, like a local enlargement of the pipe: Connection of a penstock to a large gallery for example, or the connection point of the gallery to the surge tank. This variability is probably related with the importance of water volumes exchanged at each oscillation of the surge.

Among the 3 surges (out of 21) which does not match with the statistics, one can be clearly explained by the difference between $F_{Penstock\ Load\ rejection}$ and $F_{Penstock\ Instability}$ (and probably another one too).

8. Conclusions and outlook

The statistical analysis of an extensive database of penstock resonance cases during full-load pressure surge event collected by EDF and GE Hydro has been presented in this paper. The RPRF value (Rope-Penstock resonance ratio) is defined and calculated for each case in order to classify the results. Most of the cases are corresponding to a ratio ranging in a particular interval and a physical interpretation of this ratio has been developed to explain this result.

For some hydropower-plants where a pressure surge was reported, an innovative method using PVDF wires has been applied and the details of application have been presented. This method allows easy and non-intrusive dynamic pressure measurements distributed all along the penstock. Such pressure mapping allows a fine analysis of the wave propagation during the surge event and shows the development of standing waves in the penstock with shape and frequency depending on the operating point.

Together with the intrinsic behaviour of the cavitating rope, the natural frequencies of the penstock (derived from the main hydro-acoustic frequency a/4L and depending on the geometry of penstock) plays an important role in the determination of the surge frequency and probably in the apparition of resonance. A criterion based on the “Penstock Wavenumber” PW has also been proposed to evaluate the conditions of transmission of the full-load pressure surge fluctuations along the penstock, and the location of maximum fluctuation amplitude.

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The authors:

Jean Héraud graduated as an aeronautical engineer in 1995 and joined EDF in 1997. During the last 13 years he has realized many hydraulic plant site measurements in the field of flow measurement, efficiency optimization, start-stop optimization and hydro mechanical diagnostic and troubleshooting.

Bruno Lecomte graduated as an engineer in 1990 and joined EDF in 1991. After a first job in electric system dispatching, he joined EDF hydraulic production and held several jobs in power plants operation, Hydraulic Control Center manager, Project manager. During the last 5 years, he is in charge of hydroacoustic penstocks monitoring and diagnostic / troubleshooting in transient operation.

Mathieu Comelli holds an engineering degree from Ecole Nationale Supérieure de l'Energie, l'Eau et l'Environnent de Grenoble (ENSE3, Grenoble, 2013). He joined GE in 2013 as project engineer working for mechanical and hydraulic design for hydromechanical products. He is now hydraulic engineer in charge of transient study.

Pierre-Yves Lowys graduated as an aeronautical engineer and joined Alstom (now GE) in 1997 for mechanical design and then model testing. After 5 years in Brazil and India as expert for field test and Pelton development, he is now Senior Consulting Engineer for system and multi-physics. He has performed diagnostic and troubleshooting test on more than 35 hydro projects worldwide.

Goran Pavic is Professor Emeritus, in the INSA de Lyon. He is a specialist of dynamics of pipes on which he has written many contributions.