Linear pressure profile estimation along a penstock associated with transients due to severe defects

JL Kueny¹³, G Combes², M Lourenço², V Clary¹, JL Ballester²
¹Professor, Grenoble Institute of Technology (INPG-ENSE³-LEGI), France,
²EDF - DPIH DTG MPSH, Grenoble France
³Optydro-concept, Switzerland

Abstract. The purpose of this article is to show how the pressure load profile along a penstock of an hydroplant and the corresponding flow rate is obtained from the pressure signal using a code called ACHYL CF. In particular the paper will present how it is possible to reconstruct the history of the incident after a strong transient state, in the case of two plants with Pelton turbines and one DSPCF device on a branch of the circuit. For plant_1 the DSPCF device observes an overrun of the maximal allowed pressure after the filling of the injector branch and for plant_2, a strong transient leads to the rupture of the penstock.

1 Introduction
EDF (Electricité de France) is a leading supplier of hydropower in the European Union, with an installed power capacity of 20 000 MW on the French territory. EDF’s Hydro Division operates a total of 435 hydropower plants and 550 penstocks, representing a cumulated length of roughly 260 km. The equipments mainly consist in penstocks dating back from early 20th century to the present day, with an average age of 60 years.

Due to the age of its facilities, EDF’s Hydro Division has focused on their safety and their efficiency. The SuPerHydro (“Sûreté et Performances de l’Hydraulique”) Program was launched by EDF in 2006 to guarantee the long-term safety of its hydropower facilities, particularly penstocks and gates. Moreover, EDF’s Hydro Division has launched in 2009 the RENOUVEAU Program, which aims at modernizing the methods of operation, maintenance and information system. Due to this program, large numbers of penstocks are equipped with pressure transducers linked to transient recorders. These systems are called DSPCF (which stands for “Dispositif de Surveillance de la Pression dans la Conduite Forcée”). Until year 2013 more than 200 penstocks have been equipped in France, for a target of 350 in 2016. DSPCF devices record disturbances of pressure; as soon as the pressure level reaches a significant level called "monitoring threshold", the pressure signal is acquired (each file is 10 minutes long at a sampling frequency of 40 Hz) and its waveform is stored for further analysis. Optionally, other variables are recorded, such as the stroke of the injectors.

Transient behaviors can have severe consequences for hydraulic facilities: high pressures generated during operation can damage penstocks and, sometimes, lead to their rupture. Being a unit of expertise, EDF DTG has to determine the pressure load profile along the penstock in order to establish the maintenance priorities for the pipe’s sections.

Data from all situations was processed using the transient hydraulic code BELIER based on the classic model of direct computation. With this code, the hydraulic circuit has to be modeled into several sections. Using as input data the stroke of the injector (corresponding to...
the law of flow rate), the BELIER code calculates the pressure in all the sections, thus obtaining the pressure load profile along the penstock.

This method is not straightforward, because the pressure load is not immediately available; the output data of BELIER has to be processed in every section to determine the pressure load. Moreover, it is necessary to know the flow rate, which is not always the case in the hydraulic facilities (not all DSPCFs are equipped with sensors capable of measuring the stroke of the injector and many transient situations do not involve stroke of injectors like the filling of an empty pipe section).

In order to overcome these drawbacks, EDF DTG has asked the ENSE3 School of engineers to develop a code called ACHYL CF (ACHYL CF stands for “Approche du Chargement HYdraulique Linéaire des Conduites Forcéées”). This code can model all kinds of pipe networks using singularities such as elbows, turbines, valves, etc. However, the code is based on inverse calculation: knowing the pressure at the bottom of the penstock, ACHYL CF outputs the flow rate variations in every section, as well as the pressure load profile.

The main advantage of ACHYL CF is the possibility of analyzing flow transients only in the upper part of a hydro plant, i.e. the circuit between the upper reservoir and the location where a pressure transducer is installed without taking the lower part of the network into account (which is difficult to model precisely because of the time variation feature of turbines that depends on the control condition and their state of wear).

2 ACHYL_CF software.
A software named ACHYL_CF has been developed in order to impose the pressure signal obtained on a transient recorder DSPCF as boundary condition in a pipe network model. The hydro circuit above the DSPCF recorder is modeled using a net based on nodes and branches.

![Figure 1: ACHYL_CF network elements with details of an “Inert Branch” attached to a node Ni.](image)

The nodes permit to connect the different branches of the network. At each node are attached different “Inert Branches” which concentrate classical hydro singularities like shrinkage/enlargement, elbows, valves, pumps or turbines, pipe of small length,… These singularities have small lengths in comparison with the pipes in the network and are considered as “Inert Elements” since the time of travel of a disturbance wave through it is much smaller than the computational time interval \( \delta t \). An “Inert Branch” can be connected to a Pipe Element or another “Inert Branch” or can have a free extremity. In this last case, a boundary condition singularity must be present in the corresponding branch: a “Lake” (a free surface with an imposed altitude \( z=Z(t) \)) or a “Reservoir” (a free surface with a variable altitude depending on the stored volume of liquid) or a “dead branch” (variable pressure but flow rate \( Q=0 \)) or a “pressure transducer” (p imposed, \( Q \) variable).
Two partial differential equations (the unsteady Euler equation with the conservation of mass) provide the 1D transient fluid model considered in the “Pipe Elements”:

\[ \frac{dV}{dt} + \frac{1}{\rho} \frac{\partial p}{\partial s} + g \frac{dz}{ds} + \frac{f}{2D} V|V| = 0 \]

\[ \frac{a}{\rho} \frac{\partial V}{\partial s} + \frac{1}{\rho} \frac{dp}{dt} = 0 \]

At time t, V and p are respectively the velocity and pressure at a point located at abscissa s in the pipe (altitude z). f is the friction coefficient of the pipe and D its diameter. If K is the bulk modulus of elasticity of the liquid, E the Young’s modulus of elasticity of the pipe material of thickness e, μ its Poisson ratio, the wave celerity a can be evaluated:

\[ a = \frac{[K/\rho]^{1/2}}{1 + \frac{K D}{E e} (C)^{1/2}} \]

with

\[ C = \frac{5}{4} - \mu \quad \text{Pipe rigidly anchored at both ends} \]

\[ C = 1 - \mu^2 \quad \text{Buried pipeline} \]

\[ C = 1.0 \quad \text{Pipe with expansion joints} \]

These equations are solved using a classical method of characteristics (see ref. [8], [9], [10]).

The main advantage of ACHYL_CF is that it offers the possibility to analyze flow transients only in the upper part of a hydro plant, i.e. the circuit between the upper reservoir and the location where a pressure transducer is installed without taking the lower part of the network into account, which is difficult to model precisely because of the changing feature in time of the turbines, depending on the control condition and their state of wear.

3 Plant I description

The circuit of hydro plant_1 is represented on figure 2. It has been schematized with 5 pipes, each having different lengths, different thicknesses and different diameters. Therefore their corresponding celerity is different. It varies from 856m/s to 1303m/s.

The penstock consists in 4 pipes and several singularities (valves, bends, widening/shrinkage, junctions…). Its length is 2160m and the mean wave celerity is about 1200m/s. A typical period of the waves in this penstock will be about T=4L/a=7.2 s. In its lower part, the penstock splits in 2 parallel branches which have a length of 530 m.

The upper circuit consists of a 470m long pipe between the reservoir Co, where the water level can be considered as constant and the 3-branche junction. The penstock is plugged on the lateral branch (90°). The pipe continues up to the surge tank Bo which is modelized as an axisymmetric tank which respects the evolution of the volume of water with the height (see fig. 13).
To control the ACHYLCF code result, a non linear closure of the Pelton injector has first been simulated in 20s and then the calculated pressure at the DSPCF location has been used to estimate the flow rate with the inverse mode of the code (see figure 4). The flow rate estimated with the inverse mode corresponds to the flow rate of the direct mode with an error less than 0.1 l/s.

Figure 4 Flow rate and DSPCF pressure with a simulated closure in 18 s. The imposed flow rate Q in the direct mode corresponds to the flow rate obtained using the inverse mode of ACHYLCF code, with error less than 0.1 l/s.

4 Plant I transient behavior.
The DSPCF transient signal exceeds the upper threshold of the allowed pressure in the penstock during the filling procedure of the injector branch, which is located after the spherical valve at entrance of the power house of the plant, see figure 5. The corresponding record has been used as boundary condition for the ACHYLCF plant model. The observation of the DSPCF record with the estimated flow rate obtained via ACHYLCF code permits to analyze the history of this incident, see figure 6. The incident starts at time 138s. The DSPCF pressure record reaches the upper allowed limit at time t=150s. After this moment, the time record presents the typical period related to the pipe length $T=4L/a=7.2$ s. The observed signal modulation corresponds to the period of the surface level oscillation in the surge tank related to the pipe length between reservoir Co and Bo.
The flow rate at DSPCF location, figure 6, decreases and presents an asymptotical behavior and leads to a residual flow rate corresponding to the water losses at injector when injector remains closed, see figure 7 scenario phase 2. This residual loss has been used to calibrate the surface level in the upper reservoir Co. The integrated flow rate corresponds approximately to the volume of the pipes in the branch between the spherical valve and the injector.

Three phases are observable on the flow rate evolution figure 6. The 1st phase corresponds to the filling of the pipes located between the spherical valve and the Pelton injector. When the mobile ring of the spherical valve is opened, the head loss at the flow passage reaches $\frac{P_{\text{Penstock}}-P_{\text{branch}}}{\rho g} = K_{\text{mobile ring}} q_{\text{loss}}^2$. The flow rate $q_{\text{injector}}$ of air
leakage at injector outlet is controlled by the sonic speed $C_{\text{air}}$ in this passage and is negligible compared to $q_{\text{loss}}$. If the volume in the branch between the spherical valve and the injector is $V$, the pressure $P_{\text{branch}}$ in this area will evolve following the ideal gas law $P_{\text{branch}}V = cT$ and more the volume $V$ diminish, more $P_{\text{branch}}$ increases and flow rate $q_{\text{loss}}$ will decrease at the spherical valve mobile ring passage.

When the water surface level reaches the injector (phase 2), the air leakage through the injector is replaced by water, the section of air passage is reduced and the air flow rate diminishes while $P_{\text{branch}}$ increases. During this phase $V$ is decreasing and the flow rate at DSPCF section is increasing. Pressure at DSPCF section is first more decreasing than increasing due to the inertia of the penstock.

When the air passage at injector is totally filled by the water, the velocity of water $C_{\text{water}}$ is controlled by the pressure difference between inner pipe and the extern atmosphere

$$\delta H = \frac{P_{\text{injection}} - P_{\text{atm}}}{\rho g} = \zeta_{\text{injector}} \cdot C_{\text{water}}^2$$

and the $q_{\text{injector}}$ flow rate will practically vanish. $P_{\text{branch}}$ increases and gives rise to a flow blockage at the spherical mobile ring passage. The classical oscillation of the penstock pressure related to a water hammer starts (phase 3). During this phase, ACHYLCF code permits to evaluate the loading envelope along the different pipes of the circuit, see figure 8.

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5 Plant II description

In 2012, in a French hydraulic Plant, a defect in the oleo-hydraulics circuit caused a closure of an injector in 0.28 seconds. The hog pressure levels (56 bar for 36 bar of Maximum Guaranteed Pressure) led to the rupture of the penstock. The DSPCF installed at Plant II shortly before recorded this incident: in addition to the pressure transducer, the monitoring system is equipped with a sensor that measures the stroke of the injectors. This allowed a fast analysis of the event by EDF DTG.

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![Figure 8 Envelopes of pressure along pipes (see pipe location on figure 1).](image)

![Figure 9 Location of the penstock rupture.](image)
In a first step the ACHYLCF model has been elaborated by introducing the 2 branches corresponding to the two turbines: N°1 and N°2. The injector Flow rate-Opening law has been adjusted using corresponding measurements available for this plant, figure 9. A direct mode simulation has been performed by imposing a fast closure of turbine N°2 with the simultaneous slow closure of Turbine N°1. Corresponding inverse mode calculation, see figure 13, permits to control that the model is correctly elaborated.

![Figure 10 Penstock rupture.](image)

![Figure 11 Hydro plant II equipped with two Pelton turbines and one DSPCF recorder and Flow rate-Opening adjustment at injectors.](image)

![Figure 12 Control of the inverse simulation using the calculated pressure at the DSPCF location obtained with the direct simulation.](image)
The DSPCF record is presented in figure 12. The instant $T_{\text{start}}$ corresponding to the brutal closure of turbine N°2 closure is estimated by comparing the direct ACHYLCF calculation with the DSPCF pressure record, figure 14. This closure evolution of turbine N°2 is therefore imposed for the inverse mode calculation of ACHYLCF code.

The flow rate $Q_{\text{DSPCF}}$ at DSPCF location, figure 15, presents a rapid decrease at $T_{\text{start}}$ time, related to the fast transient increase of the pressure. The turbine N°1 injector is still open, and $Q_{\text{DSPCF}}$ therefore recovers a value corresponding to the injector loss coefficient of turbine N°1. When the pressure wave created by the water hammer related to turbine N°2 closure returns to DSPCF location, it results in a fast pressure decrease with a fast increase of the flow rate. The pressure evolution estimated using ACHYLCF code permits to detect a pressure lower than absolute 0 bar in the rupture area of the penstock, see figure 15. At the present time cavitation is not taken into account by ACHYLCF code, but the apparition of cavitation which will be followed by corresponding implosion phase might explain the rupture of the penstock.
6 Conclusion

These two critical events recorded by the EDF’ DSPCF devices have shown the interest of using an inverse transient simulation code like ACHYLCF to explain the history of the events. These results also show that the ACHYL_CF code offers the possibility to determine the mechanical stress imposed on the penstock during transient states when using the inverse calculation. This major advantage makes this software a very useful tool to control the hydro power plant safety during critical events, using the only known data, i.e. the recorded pressure signal.

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