Experimental Hydro-Mechanical Characterization of Full Load Pressure Surge in Francis Turbines

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Abstract. Full load pressure surge limits the operating range of hydro-electric generating units by causing significant power output swings and by compromising the safety of the plant. It appears during the off-design operation of hydraulic machines, which is increasingly required to regulate the broad integration of volatile renewable energy sources into the existing power network. The underlying causes and governing physical mechanisms of this instability were investigated in the frame of a large European research project and this paper documents the main findings from two experimental campaigns on a reduced scale model of a Francis turbine. The multi-phase flow in the draft tube is characterized by Particle Image Velocimetry, Laser Doppler Velocimetry and high-speed visualizations, along with synchronized measurements of the relevant hydro-mechanical quantities. The final result is a comprehensive overview of how the unsteady draft tube flow and the mechanical torque on the runner shaft behave during one mean period of the pressure oscillation, thus defining the unstable fluid-structure interaction responsible for the power swings. A discussion of the root cause is initiated, based on the state of the art. Finally, the latest results will enable a validation of recent RANS flow simulations used for determining the key parameters of hydro-acoustic stability models.

1. Introduction

When operating a hydraulic machine outside its best efficiency point (BEP), the flow leaving the runner carries a significant residual swirl. The resulting inhomogeneous pressure distribution leads to the formation of cavitation. At full load ($Q > Q_{\text{BEP}}$), the latter takes the shape of an axisymmetric cavitation vortex rope attached to the runner hub. As the cavity grows with a decreasing pressure level in the draft tube, the hydro-acoustic Eigenfrequencies may sink to a critical level and the system enters self-oscillation. Violent pressure fluctuations are then observed throughout the system, which translate into dangerous power swings on the generator side. Their peak-to-peak amplitude typically reaches several percentage points with respect to the nominal output. This is naturally unacceptable in large units, that produce several hundred Megawatts and are possibly connected to long electric transmission lines.

The phenomenon was reported as early as the 1940s \cite{1}. The first experimental descriptions from reduced scale model testing are from the late 1980s \cite{2,3}. Analytical \cite{4,5,6,7}, 1-D hydro-acoustic \cite{8,9}, as well as numerical \cite{10,11} analyses of the swirling flow or/and the associated unstable behavior followed over the years (this list being by no means exhaustive). How the physics are represented in these models is crucial, if one day the behavior of the machine is to
be accurately predicted at any given scale. Therefore, a thorough investigation of the sustaining mechanisms and the underlying causes of the self-oscillation is necessary. This was performed in one of the 6 scientific work packages of the HYPERBOLE research project, funded by the European Commission in its 7th Framework Program. The general objective of the project is to move towards a smooth integration of a large portion of renewable energies in the existing power network by taking advantage of the regulatory capacities of hydropower and pump-storage plants. The project coming to an end, this article provides a condensed overview of the research (see Section 2), the main results (Section 3 and Section 4), the problems to be solved and the corresponding perspectives (Section 5) in the field of full load surge.

2. Methodology

2.1. Experimental setup and measurements

Firstly, the draft tube flow was extensively characterized for stable and unstable operating points. The term unstable refers to the occurrence of full load pressure surge. The notion of stability is further discussed in Section 4. The instrumented model installed on the EPFL test rig PF3 for the Laser Doppler Velocimetry (LDV) and the Particle Image Velocimetry (PIV) measurements is shown in Figure 1. More details are found in [12, 13] for the PIV and [14, 15] for the LDV configuration, respectively. For the draft tube flow visualizations in the top row of Figure 2, the setup was similar to the one in Figure 1(b) with a different camera and an additional uniform LED backlight source on the other side of the Plexiglas cone in order to enhance the contrast between the liquid and the gaseous phase. For the visualization of the inter-blade flow from below, shown in the bottom row of Figure 2, the high-speed camera was tilted and synchronized with a stroscopic light. A different water-box was used to minimize the optical distortion, for which the flat surface faced the inter-blade channels. The corresponding setup is not shown here but described in [16].

![Draft tube flow survey on a 1:16 reduced scale model of a Francis turbine.](image)

Figure 1: Draft tube flow survey on a 1:16 reduced scale model of a Francis turbine.

The operating conditions are defined by the non-dimensional speed factor $n_{ED} = (n \cdot D) / \sqrt{E} = 0.288$ and the discharge factor $Q_{ED} = Q / (D^2 \sqrt{E}) = 0.26$, where $Q$ is the discharge, $n$ the rotational frequency, $D$ the runner outlet diameter and $E$ the specific hydraulic energy. The non-dimensional cavitation number, expressing the pressure in the draft tube as a function of the turbine’s level setting, corresponds to the one on the real size machine ($\sigma_{\text{plant}} = 0.11$) for the unstable operation. It can be adjusted with a vacuum pump over the free surface of the downstream tank. For the stable configuration, the pressure in said tank was set to atmospheric. The measurements were synchronized by sharing a common trigger.

2.2. Data processing

All quantities were averaged with respect to the wall pressure signal in the draft tube cone. The procedure is described in detail in [17] and consists of isolating the different cycles of a signal
according to the locations of the characteristic pressure peaks. The cycles are then superposed and the data averaged in $10^2$ sub-windows over one period. This offers a comprehensive impression of how the system behaves during one typical period.

The LDV measurements taken during the self-oscillation were averaged in the same manner. Thanks to the synchronized start, each velocity measurement has a unique time stamp within the data acquisition. Based on its relative position with respect to the period of the pressure cycle it was recorded in, the measurement can be attributed to one of the defined sub-windows and then the mean value of all the other measurements that fall into that same sub-window is calculated. The result is a pressure-phase averaged evolution of the tangential and the axial velocity components $Cu$ and $Cm$ at a given radial position. The latter can then be integrated over all the radial measurement positions on each of the two streamwise locations shown in Figure 1(a) to yield the axial fluxes of angular and axial momentums, the ratio of which shall be defined as the swirl number for further considerations (for details please referred to [15]).

3. Results

As a starting point, Figure 2 shows the characteristic breathing motion of the cavitation vortex rope as well as the formation and collapse of cavitation on the runner blades at several equally spaced instants over one pressure oscillation period. It is noted that the cavitation on the runner blades develops seriously between the instants (c) - (g), corresponding to the collapsing phase of the vortex rope. The blade cavitation also starts shedding into the draft tube flow in the form of small bubbles, which darken the images in the top row of Figure 2. Once the blades have been cleared at instant (h), the vortex rope reshapes again from above.

![Figure 2: Dynamics of the cavitation vortex rope in the draft tube cone (top) and the blade cavitation (bottom) at 8 equally spaced instants during 1 cycle of the instability.](image)

The instants (a) - (h) in Figure 2 may be put into relation with the hydro-mechanical data based on their relative position within the period of the pressure cycle they were recorded in. These are represented by vertical dashed lines in Figure 3(a) and Figure 3(b), which contain the pressure-phase averaged evolutions of the swirl number $S_n$ in the draft tube at the 2 streamwise locations shown in Figure 1(a) as well as the mechanical torque factor $T_{ed} = T_{in}/(\rho D^3E)$, together with the wall pressure factor $c_p = (p - \bar{p})/(\rho E)$. Figure 3 offers a compact view on how the hydraulic and mechanical parts of the machine evolve during a mean period $\bar{T}$ of the surge. This clears the important task of establishing the fluid-structure interaction mechanisms, but does not answer the question of the root cause for the instability.

For the purpose of finding out what ultimately causes full load pressure surge, the transition is studied numerically with a RANS simulation [18]. Figure 4 shows a stable draft tube flow at an atmospheric pressure in the downstream tank, which was characterized by PIV in order to validate the numerical model. It is noted that a slender, axisymmetric cavitation vortex rope
Figure 3: Pressure-phase averaged hydro-mechanical system behavior during full load surge.

is already present at this point. When the pressure in the draft tube is decreased to reach \( \sigma_{\text{plant}} \), the cavity will grow in its diameter, start fluctuating and eventually enter self-oscillation as shown in Figure 2. The color chart in Figure 4 to the right displays the magnitudes of the mean velocity field resulting from 600 measurements in a vertical (meridional) plane of the draft tube. Even if the light sheet generated by the Laser partly crosses the vortex rope and vectors are calculated on the other side, only the region between the left cone wall and the vortex rope edge is deemed trustworthy. Measurements were also taken in two horizontal cross-sections of the draft tube, at the same streamwise locations as the LDV measurements. The processing of the PIV data is however an ongoing task at the time of writing of this paper and will be the object of future publications.

Figure 4: Draft tube flow visualization (left), single image from the PIV camera (middle) and amplitudes of the mean velocity field (right) at \( \sigma = \text{atm} \) for the validation of RANS models.

4. Discussion
As previously indicated, the breathing motion of the vortex rope is governed by the swirl variation, which is in turn caused by the modification of the relative flow angle at the runner exit due to the formation of significant volumes of cavitation on the blades. The blade cavitation also changes the hydrodynamic properties of the runner and thus the transfer of momentum to the shaft, represented by the mechanical torque. The torque peak between instants (c) and (d) appears shortly after the vortex rope reaches its maximum volume. \( T_{\text{ED}} \) then decreases while the cavitation on the runner blades becomes dominant and starts growing again with the vortex rope. In other words, the mechanical torque appears to be well synchronized with the vortex rope volume, considering a slight delay due to the mechanical inertia of the system.
The cause for the instability has been debated by several authors in the past and a destabilizing role of the pressure recovery is brought up regularly \cite{11, 12, 16}. Indeed, since the pressure in the downstream tank is constant, any discharge increase from the runner would have to be compensated by a drop in the draft tube pressure and thus by a cavity growth. And in the vicinity of one of the hydro-acoustic Eigenfrequencies, the slightest perturbation might cause this positive feedback to trigger the kind of self-excited hydro-mechanical oscillation shown in Figure\ref{fig:2} and Figure\ref{fig:3}. The further experimental and numerical examination of the transition shall hopefully bring more clarity to this discussion.

5. Conclusion and perspectives

The unstable fluid-structure interaction mechanisms causing dangerous power swings in Francis turbines at full load were identified experimentally in the course of the HYPERBOLE research project. Based on the obtained data, RANS models are being validated for the closer numerical study of the pressure surge onset, its root cause as well as for the identification of the key parameters of 1-D hydro-acoustic flow models used for stability analysis.

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