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Fluid–structure interaction mechanisms leading to dangerous power swings in Francis turbines at full load

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ABSTRACT

Hydropower plants play an important regulatory role in the large scale integration of volatile renewable energy sources into the existing power grid. This duty however requires a continuous extension of their operating range, provoking the emergence of complex flow patterns featuring cavitation inside the turbine runner and the draft tube. When the power output is maximized at full load, self-excited pressure oscillations in the hydraulic system may occur, which translate into significant electrical power swings and thus pose a serious threat to the grid stability as well as to the operational safety of the machine. Today's understanding of the underlying fluid–structure interaction mechanisms is incomplete, yet crucial to the development of reliable numerical flow models for stability analysis, and for the design of potential countermeasures. This study therefore reveals how the unsteady flow inside the machine forces periodic mechanical loads onto the runner shaft. For this purpose, the two-phase flow field at the runner exit is investigated by Laser Doppler Velocimetry and high-speed visualizations, which are then compared to the simultaneously measured wall pressure oscillations in the draft tube cone and the mechanical torque on the runner shaft. The results are presented in the form of a comprehensive, mean phase averaged evolution of the relevant hydro-mechanical data over one period of the instability. They show that the flow in the runner, and thus the resulting torque applied to the shaft, is critically altered by a cyclic growth, shedding and complete collapse of cavitation on the suction side of the runner blades. This is accompanied by a significant flow swirl variation in the draft tube cone, governing the characteristic breathing motion of the cavitation vortex rope.

1. Introduction

The extension of the operating range of hydroelectric powerplants is essential in guaranteeing a smooth integration of new and renewable energy sources into the existing power grid (Bélanger and Gagnon, 2002; Gaudard and Romerio, 2014). The stabilizing ancillary services provided by the utilities moreover represent a lucrative source of revenue (Deb, 2000; Shayeghi et al., 2009). The geometry of Francis turbines, representing over 60% of the installed hydropower capacity worldwide, is however optimized for their Best Efficiency Point (BEP). When the flow rate in the machine is changed in order to generate less or more electrical power than at the BEP, a significant residual swirl in the flow at the turbine runner outlet is observed, which results in inhomogeneous pressure distributions in the draft tube. The development of cavitation is thus favored, potentially inducing hydroacoustic instabilities with high amplitude pressure fluctuations. At full load, when the electrical power output is maximized, the pressure oscillations translate into dangerous electrical power swings, documented as early as the 1940s (Rheingans, 1940). The peak-to-peak amplitude of these

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fluctuations can reach up to 5–10% of the rated power, which is naturally unacceptable for large machines generating several hundred Megawatt, connected to long electric transmission lines.

The characteristics of this instability are defined by the hydraulic conditions, as observed during extensive reduced scale model testing. This is illustrated by the fact that the dominant oscillation frequency depends linearly on the pressure level in the draft tube (Müller, 2014) and by extension on the volume of the axisymmetric cavitation vortex rope which is formed at the runner outlet. The presence of vapor however decreases the local wave speed (Ruchonnet et al., 2012; Landry et al., 2016), thus suggesting that the system excites itself at one of its hydroacoustic Eigenfrequencies. A discussion of the underlying physical mechanisms, by which the self-excited oscillations of the hydro-mechanical system are sustained, and a detailed description of the unsteady flow field in the draft tube cone are provided by Müller et al. (2012, 2013, 2014).

Despite the dominant hydraulic role, the face of the instability in a real size power plant is of structural nature and generates oscillations of the mechanical torque and hence the electrical power. Several studies exist on how structural properties are affected by the surrounding flow of an incompressible fluid in general (Münch et al., 2010; De La Torre et al., 2013; Presas et al., 2016), and by the presence of cavitation in particular. The added mass effect for instance, which alters the hydrodynamic performances of the runner, is shown to be significantly reduced by the development of cavitation on a generic hydrofoil, as reported by De La Torre et al. (2013). It is furthermore to be expected that the cavitation modifies the inertia and the rotational energy of the fluid, which on their part are known to influence the dynamic behavior of hydraulic turbine rotors (Jansson et al., 2012).

The described phenomenon, commonly referred to as full load pressure surge, involves a number of hydraulic and mechanical variables, standing in complex interaction. The experimental approach presented in this paper offers a comprehensive way of describing the unstable fluid–structure interaction mechanisms between the unsteady draft tube flow and the runner shaft. The swirl number, representing the angular momentum in the presumably axisymmetric flow, is calculated at two different streamwise locations of the draft tube cone based on Laser Doppler Velocimetry (LDV) measurements at over thirty radial positions between the cone center and the cone wall. Each LDV measurement is synchronized with the acquisition of a reference wall pressure signal and the mechanical torque. The resulting axial and tangential velocity, pressure and torque data are then averaged with respect to the mean phase of the reference wall pressure signal. This enables a direct comparison between the flow swirl, the pressure and the torque. Together with high-speed visualizations of the cavitating draft tube and blade channel flow, the underlying mechanism of fluid–structure interaction is finally defined and the question of how the self-excited pressure oscillations cause the electrical power swings is answered.

The physical phenomenon at hand is characterized in detail in Chapter 2, by describing the self-oscillation of the hydro-mechanical system with pressure and torque signals in the time domain as well as with high-speed flow visualizations. The experimental setup, the instrumentation as well as the data processing methodology are introduced in Chapter 3. The results in the shape of pressure phase averaged velocity profiles as well as swirl and torque variations are presented in Chapter 4. The unstable fluid–structure mechanism and possible causes for the onset of the instability are then discussed in Chapter 5, followed by some concluding remarks and perspectives in Chapter 6.

2. Hydro-mechanical self-oscillations in Francis turbines

The present test case is an existing Francis turbine with a rated power output of 444 MW, experiencing serious full load pressure surge with power swings of more than 30 MW peak-to-peak. The unstable behavior is reproduced on a 1:16 reduced scale physical model of that turbine with a specific speed of $\nu = 0.27$, fulfilling the hydraulic similitude according to IEC standards (1999). Fig. 1 displays the reduced scale model with its main components. The inlet pipe feeds the water to the spiral case, where it is circumferentially distributed and injected into the runner through the stay vanes and the guide vanes. The flow exits the runner into the Plexiglas draft tube cone and is, then, redirected in the elbow towards the draft tube diffuser. The installation of the model on the EPFL test rig PF3 enables a very accurate simulation of the complete machine. The test rig is operated in closed loop configuration, where the head is generated by two axial double-volute pumps. A generator connected to the model runner regulates the rotating

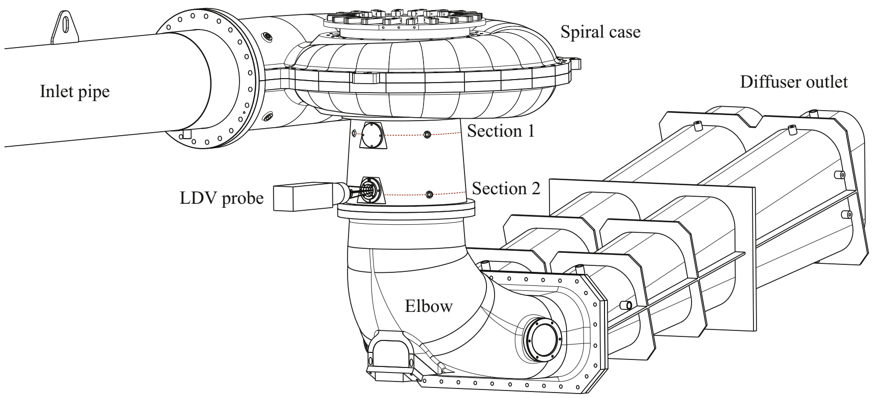

Fig. 1. Reduced scale physical model of a Francis turbine with flow survey instrumentation.