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Swirling flow in a hydraulic turbine discharge cone at different speeds and discharge conditions

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ABSTRACT

An experimental investigation of the cavitating turbulent flow in a simplified hydraulic turbine was carried out to examine flow features in a wide range of speed and discharge conditions. A swirling device that allows reproducing the speed distribution behind the runner of a real turbine was manufactured using a rapid 3D prototyping technology. Laser Doppler velocimetry was used to measure both axial and tangential velocity components at the runner outlet for 96 operating regimes. The limitations of the swirl number used for swirling flow characterization through swirl free speed and discharge conditions were investigated. Particular attention was paid to the instability of the precessing vortex rope in the transition regime at a low swirl number. The boundaries of the regime with an aperiodic pressure surge in terms of the swirl number were defined, contributing to insight into the stability of swirling flow in hydraulic turbines.

1. Introduction

The flexible operation of hydraulic turbines is in demand for new renewable energy sources integrated in an electrical grid. The capability of hydropower plants to quickly change their output power by hundreds of megawatts in a short time is useful and used repeatedly. This ability is extremely necessary when using such unstable technologies as wind generators or solar batteries in an electrical grid. Despite the fact that turbines are designed for optimal operating conditions, the rapid regulation of a grid is usually possible when shifting toward non-optimal operation modes. Operating conditions beyond optimal ones, in which a turbine is manufactured (runner geometry, draft tube, etc.), are classified by the relationship between Q/Q_{BEP} discharge at the best efficiency point (BEP) and current discharge at a constant runner speed. In non-optimal (upper part-load, part-load, deep part-load, full-load) or transient regimes, the flow behind the runner has a residual angular momentum, which, in combination with a deceleration in the expanding part of the draft tube leads to the formation of a cavitation vortex rope in the turbine draft tube. At part load it rotates around a central axis and generates powerful pressure pulsations, which can result in a resonance as well as reducing the efficiency and reliability of the hydraulic unit. Interacting with the draft tube elbow, the vortex rope creates pressure disturbances in the entire flow path. The strong influence that the vortex rope has on the power plant performance requires studying the mechanism of the precessing vortex core (PVC) formation and controlling its impact, which is necessary for advancing hydropower plant efficiency and preventing undesirable vibrations.

Pressure surge in hydroelectric power plants has been studied for almost a century, beginning with one of the first works by Rheingans [1], who documented that pressure oscillations in a hydraulic turbine translated into dangerous electrical power swings. Since then, the problem of non-stationary pulsations of pressure and power during the operation of hydro turbines in various regimes has been significantly covered in the literature [2–5]. In view of the complexity of conducting any quantitative measurements on real turbines, reduced scale turbine model are commonly employed. Also a simplified modeling of different parts of the hydraulic turbine is applied at working on the design of hydro turbine systems. In particular, when studying the structure of flow in draft tubes, the method of installing a stationary swirling device, which creates a flow at the inlet to the draft tube, similar to the flow behind a real hydraulic turbine at partial discharge [6]. Investigations on a reduced scale model or studies of flow regimes in simplified models, where only the velocity distribution behind the runner of real turbines is simulated, opens up great opportunities for understanding complex phenomena that occur in full-scale hydro turbines. The pressure surge amplitude cannot be directly transposed from the prototype to a real turbine, but one can draw general conclusions and generalize the information for various regimes. A significant amount of experimental data has been accumulated in simulating the flow in hydraulic turbines using a swirl generator instead of spiral case,

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Nomenclature

u	axial velocity (m/s)
w	tangential velocity (m/s)
V	bulk velocity (m/s)
N	runner speed (rpm)
Q	flow rate (m^3/s)
N_0	swirl-free runner speed (rpm)
Q_0	swirl free flow rate (m^3/s)
Q_{ED}^0	swirl-free discharge factor (–)
n_{ED}	speed factor (–)
S	swirl number (–)
R	radius (m)
r	radial coordinate (m)
Re	Reynolds number (–)
Sh	Strouhal number (–)
G_θ	axial flux of azimuthal momentum ($kg{\cdot}m^2/s^2$)
G_x	axial flux of axial momentum ($kg{\cdot}m/s^2$)
ω	angular runner speed (rad/s)
R_{in}	internal runner radius (m)
R_{ex}	external radius (m)
U'	root mean square of the axial velocity fluctuations (m/s)
W'	root mean square of the tangential velocity fluctuations (m/s)
BEP	best efficiency point
PVC	precessing vortex core
PSD	power spectral density

stay and guide vanes, which is developed in order to investigate the flow instability [7–13].

A partial description of the different flow and vortex patterns can be found in a review paper by Nishi et al. [14]. Nicolet et al. investigated the features of flow structure in upper part load for loads between 0.7 and 0.85 Q_{BEP}, and pressure fluctuations at higher frequencies 2 to 4 times the runner rotational speed were detected [15]. In a number of studies, the phenomenon of a twin vortex rope was considered [4,16]. The splitting of a precessing vortex rope into a twin-spiral vortex with higher precession frequency is observed. Muller et al. [3] contributed to the description of self-excited pressure oscillations observed at full-load conditions when a turbine operates at full capacity and increased understanding of the underlying fluid–structure interaction mechanisms leading to power swings. The effect of cavitation is important both in terms of increasing the efficiency of turbines and their safe operation. It has been indicated that the positive slope on the pump performance curve of pump-turbine instability can be affected by cavitation conditions [17].

Modern optical techniques of flow diagnostics, such as particle image velocimetry (PIV) [18–20], laser Doppler velocimetry (LDV) [3,20,21], and high-speed visualization have been widely used to study the complex structure of turbulent swirling flow, which together provide a qualitative and quantitative representation of the flow. Using the PIV system together with phase averaging makes it possible to determine the position of the PVC center and to track its trajectory in one revolution of precession in different sections for different Q/Q_{BEP} ratios [18]. The authors noted that amplitudes of the synchronous pressure pulsations are strongly dependent on the trajectory and the strength of the PVC; thus, it plays a key role in the interactions of the secondary flow in the draft tube elbow. Tridon et al. [19] paid attention to measuring the radial velocity component, which is usually rarely measured due to the complexity of the required measurement setup and significant curvature of the draft tube cone for LDV application. Nevertheless, the use of precise calibration targets and the PIV system made it possible to measure this component. A strong asymmetry of the radial velocity has been shown, which is usually not taken into account in analytical models.

Along with experimental work, analytical theories were developed to describe swirling flows in order to predict flow characteristics. In a number of works, one-dimensional or three-dimensional models are presented that allows one to describe the pulsation characteristics of the flow to some extent [22–26]. Kuibin et al. [24,25] have derived an analytical model to predict the time-averaged velocity profile in a conical part of a draft tube and the frequency of the vortex rope as a function of the discharge coefficient. It was shown that a helical vortex model can correctly predict the swirling flow unsteadiness, such as precession frequency and level of draft tube wall pressure pulsations. Alligne et al. [23] developed a one-dimensional draft tube model to predict cavitation surge phenomenon in part load and full load conditions. The model is derived from flow momentum and continuity equations, including convective terms that were not considered earlier. Susan-Resiga et al. [26] developed an analytical representation of the swirling flow, taking the discharge coefficient as an independent variable. It was found that the investigated mean flow can be accurately represented as a superposition of three elementary vortices (a rigid body rotation motion, and two Batchelor vortices).

Ciocan et al. showed [27] that draft tube losses can be minimized by optimizing runner outlet flow. They proposed a new runner model where the relative flow angle is expressed by means of a swirl-free velocity profile. The model provides swirling flow profiles consistent with hydraulic turbine operation. This approach can be used for optimizing the runner for a wide range of operating regimes. An interesting approach to the description of the physical mechanism leading to the formation of PVC was considered in [28]. Based on linear global stability analysis of the time averaged flow field, the vortex rope is considered as a global unstable eigenmode – the result of a helical disturbance, which is developed around the time averaged flow field.

Another way to more deeply understand the complex structure of the flow is the method of computational fluid dynamics (CFD), based on various models (RANS, URANS, LES, DES, etc.), which have also been significantly improved [29–33]. In addition to geometry optimization problems [27,34,35], numerical simulation methods provide information on the flow structure that cannot be obtained from experiments [36]. Despite the advantages of numerical simulation, it requires ongoing verification by experimental data.

Returning to experimental work, one should pay attention to an interesting and still unexplained phenomenon called “pressure shock”, which presents a particular interest. This phenomenon is mentioned in the literature in the context of the partial collapse of a cavitation vortex rope. When a PVC cavity is rapidly reduced to zero volume, an intense pressure wave is created. A “shock phenomenon” has been reported from different turbine prototypes and presumably associated with a transition between different vortex shapes [2,37]. Dörfler et al. [37] mention that “pressure shock” occurs near the upper part load at Q/Q_{BEP} close to 0.85, when the regular corkscrew vortex is not supported. In confirmation of this, it was found that the “pressure shock” is also observed as a result of unstable PVC pattern in the regime with a low swirl parameter [38]. An overlap of vortex spiral and subsequent reconnection lead to formation of a cavitating vortex ring, which is the source of strong aperiodic impacts in a draft tube. The vortex reconnection process leading to the formation of vortex rings is described in detail in [39]. In [38], a high-speed flow visualization was performed in a simplified draft tube model and synchronized with the measurement of pressure pulsations on the draft tube wall. For the first time, it was possible to associate a vortex ring separated from a vortex rope with aperiodic “pressure shock”. Subsequent work [40] demonstrates the visualization of the vortex ring phenomenon at experiments in a scale model of a real Francis hydro turbine. It should be noted that only