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Detailed numerical investigation of a Kaplan turbine with rotor-stator interaction using turbulence-resolving simulations

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ABSTRACT

The U9 Kaplan turbine is simulated at two operating conditions using conventional and non-conventional URANS models and a hybrid URANS-LES method. All clearances are included in the computational domain, such as the guide vane clearances, the runner blade tip-clearances, and the runner blade hub-clearances at both the leading and trailing edges. A dynamic mesh is used together with the sliding General Grid Interface (GGI) to include the effect of the rotating runner. High-quality block-structured meshes are used to simulate the flow at the best efficiency point (BEP) and part load (PL) conditions with $Re = 1.6 \times 10^6$ and $Sr = 0.25$, and $Re = 1.39 \times 10^6$ and $Sr = 0.6$, respectively. The swirl number, Sr, is moderately low at BEP so that no vortex breakdown occurs, while it is high enough at PL to create a helical precessing *vortex rope* due to the vortex breakdown. The RNG $k-\epsilon$ model is employed as a conventional eddy-viscosity model. The explicit algebraic Reynolds stress model coupled with the SST $k-\omega$ model (EARSM) and the SST $k-\omega$ model with curvature correction modeling (SSTCC) are implemented and evaluated, as non-conventional URANS models. They are relatively easy to implement, economically tenable, and include more physics than the conventional turbulence models. The delayed detached eddy simulation method, coupled with the Spalart–Allmaras turbulence model (DDES-SA), is applied to gain a deep insight of the details of the flows. The DDES-SA simulations resolve the turbulent structures in the free-stream, but are three orders of magnitude more expensive than its URANS counterparts. The mean velocity components and their fluctuating parts are validated using experimental data. The URANS models are consistent with respect to the mean velocity at BEP, while only the non-conventional URANS models predict the mean velocity well at PL. The RNG $k-\epsilon$ model particularly fails to capture the velocity fluctuations at BEP, while the non-conventional URANS models resolve the fluctuations remarkably well. The DDES-SA model predicts the mean velocity very well both at BEP and PL. The model accurately resolves the velocity fluctuations at BEP, while they are slightly underpredicted at PL.

1. Introduction

Hydropower plants are the most prominent resource in the procurement of renewable energy. They regulate the power in the energy system. The fixed-speed turbines perform most efficiently at the design condition which represents the best combination of the runner speed, head and discharge. At the design condition, the so-called best efficiency point (BEP), water turbines generally operate with a small residual swirl entering the draft tube and without flow separations from the hub or the draft tube wall (Javadi and Nilsson, 2014b). At off-design condition, both at high-load (HL) and part-load (PL), the flow leaves the runner with a large residual swirling component (Javadi and Nilsson, 2015b). The hydraulic efficiency drastically decreases as the residual swirl increases, and the instability of the swirling flow leads to strong low-frequency pulsations which are not well-understood. The double-regulated Kaplan turbine stays close to the BEP efficiency by an adjustment of both the guide vane and runner blade angles with the flow rate. The key advantage of the axial-flow Kaplan turbine is the ability to operate at above 90% efficiency at low heads and high rotational speeds. The available range of runner blade angle adjustment is usually selected in a way as to permit high efficiency and a controlled residual swirl in the foreseen load range. Although the Kaplan turbine has a wide range of operation it may still have a significant residual swirl at PL. At PL, the range of flow where the draft tube swirl is organized to a vortex rope with a well-defined frequency is between 75 and 88% of Q_{BEP} (Dörfler et al., 2013). Compared to Francis turbines, this range is much narrower and closer to the best-efficiency condition (Dörfler et al., 2013).

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(Javadi et al., 2014; Javadi and Nilsson, 2015b) studied different level and direction of swirl in a conical diffuser with rotor-stator interaction and showed that the size and the rotation direction of the vortex rope depend on the level of the residual swirl in the draft tube. If the swirl exceeds a certain level, an upstream separation from the hub disrupts the formation of the vortex rope. In this case the on-axis stagnant region occupies a large part of the draft tube. The size of the on-axis stagnant region is a function of the guide vane opening but the pressure pulsation intensity is a function of the discharge. The phenomenon gets stronger at large runner blade opening angles (Dörfler et al., 2013). There are two additional transient phenomena in hydraulic turbines:

- Pulsations due to the rotation of the runner, its wake propagations and interactions with stay vane and guide vane wakes, spiral casing, and draft tube bend.
- High-frequency pulsations caused by Von Kármán vortices in the wakes of runner blades, stay vanes and guide vanes.

The second phenomenon affects the first one, such that the Von Kármán vortices from the guide vanes at a very large opening may noticeably interfere with the rotating flow field in the runner. Thus, the effect of the guide vane wakes on the runner flow is two-fold. Firstly, the static pressure field is disturbed by a local pressure drop in each wake. Secondly, the flow angle is locally disturbed, causing variations in the incidence angle at the tip region of the runner blade leading edge. The effect of the guide vane wakes on the pressure field in a Kaplan runner should be captured by the numerical rotor-stator interaction technique. Only handful detailed numerical studies of a Kaplan turbine with rotor-stator interaction are available in the literature.

Among various methods, the Unsteady Reynolds-Averaged Navier–Stokes (URANS) met-hod developed and emerged over decades as the most popular and economically tenable CFD framework in hydropower engineering using mainly proprietary codes. Thus, the knowledge about URANS is limited to the simplest (most robust) linear eddy-viscosity models which are available in the proprietary codes. Javadi et al. (2015) implemented and studied the Spalart and Shur (1997) curvature-correction modeling method coupled with the SST $k-\omega$ model (Smirnov and Menter, 2009) in different bladed geometries. They showed that the consideration of the streamline and surface curvature significantly improves the quality of the prediction of the mean velocity and the root-mean-square of velocity fluctuations. A drawback of this method is that the model modifies the production term in the transport equations by a multiplier. The multiplier is based on the strain and vorticity rate, which in the case of strong velocity fluctuations (Girimaji, 1997) makes the models unable to detect or even kills the unsteadiness (Javadi et al., 2015). Reynolds Stress Models (RSM) have the potential to significantly improve the flow predictions by resolving anisotropy and incorporating more sensitivity and receptivity of the underlying instabilities and unsteadiness. Since they are difficult to use they are not widely used in industry. Most of the RSMs are not robust for highly swirling flows because of instability in the rapid part of the pressure-strain term in the transport equation. Speziale–Sarkar–Gatski's (SSG) (Speziale et al., 1991) linearised quadratic solution of the term makes the model potentially a good candidate for such flows (Gavrilova et al., 2016). The Elliptic-Blending RSM (Manceau, 2015) is another adequate option for highly swirling flows. This model slightly overestimates the on-axis recirculation region. In spite of considering the underlying physics, both models (SSG and Elliptic-Blending RSM) are difficult to use with rotor-stator interaction. The Explicit Algebraic Reynolds Stress Models (EARSMs) are simplified RSMs that are much more numerically and computationally robust and have been found to be comparable to standard two-equation models in computational effort (Wallin and Johansson, 2000). The EARSMs assume that the Reynolds stress tensor can be expressed in the strain and vorticity rate tensors.

Making URANS more sensetive to instabilities is another approach to resolve the anisot-ropic and highly dynamic character of the vortical structures of turbulent swirling flows. Among hybrid URANS-LES methods, Menter and Egorov (2010), and Jakirlić and Maduta (2015) introduce additional turbulence scales representing higher frequency spectral region, so-called scale-adapting simulations (SAS). Girimaji (2006) solves transport equations with averaging over only a part of the turbulence spectrum (PANS). Detached-eddy simulation (DES) is another promising hybrid URANS-LES strategy for swirling flow (Javadi and Nilsson, 2015b; Gavrilova et al., 2016; Javadi and Nilsson, 2014a; Javadi et al., 2016; Minakov et al., 2015). The DES model was proposed in which d is taken as the minimum of the RANS turbulent length scale and the cell length $\Delta = \max(\Delta x_r, \Delta x_\theta, \Delta x_a)$, i.e.

$$\widetilde{d} = min(d, C_{des}\Delta), \tag{1}$$

where Δx_r, Δx_θ and Δx_a denote the cell length in the three grid directions r, θ and a. The constant C_{des} is usually set to 0.65. It is capable of simulating internal flows dominated by large-scale detached eddies at practical Reynolds numbers. The delayed DES (DDES) methodology is proposed by Spalart et al. (2006) to detect the boundary layers and to switch the turbulent length scale from a RANS length scale (d) to a LES length scale (Δ) when the grid is sufficiently fine. This is done even if the wall-parallel grid spacing would normally activate the DES limiter (Spalart, 2009). Javadi and Nilsson (2015a) showed that DDES is still sensitive to the wall-parallel resolutions in highly swirling flows. They reported that the model does not switch to the LES mode for a coarse wall-parallel resolution. It means that if the grid is too coarse in a wall-parallel direction, the DES limiter does not switches to LES mode out of the boundary layer. Javadi and Nilsson (2015b) studied high- and low-Reynolds eddy-viscosity models, a hybrid URANS-LES, model and a LES model in a flow similar to that in a Francis turbine operating at part load. The hybrid URANS-LES simulations were up to two orders of magnitude more expensive than those with the eddy-viscosity models. They concluded that RNG $k-\epsilon$ among the conventional eddy-viscosity models and DDES coupled with Spalart–Allmaras (DDES-SA) among hybrid modeling techniques offer the best results. The high level of unsteadiness in the flow field necessitates the utilization of hybrid turbulence treatment to predict the small-scale structures. Javadi et al. (2016) studied a wide range of swirl in a conical diffuser generated by a rotor-stator interaction. They reported that when the swirl number exceeds 0.5 the conventional eddy-viscosity models fail to predict the correct size of the on-axis recirculation region. The swirl number is defined as

$$Sr = \frac{\int_0^R U_\theta U_a r^2 dr}{R\int_0^R U_a^2 r dr}, \tag{2}$$

where U_a is the axial velocity, U_θ is the tangential velocity and R is the cross-section radius.

The present work encompasses the simulation of the U9 Kaplan turbine model using RNG $k-\epsilon$ (a conventional eddy-viscosity model) EARSM and SSTCC (non-conventional eddy-viscosity models) and DDES-SA. The paper is original in the following aspects:

- A hybrid URANS-LES model (DDES-SA) and the non-conventional EARSM and SSTCC eddy-viscosity models are implemented and used to study a full Kaplan turbine with all clearances included in the computational domain.
- A dynamic mesh is conducted using an open source code to mimic the realistic conditions at BEP and PL.

The paper consists of a description of the flows at both conditions (Section 2), the details of the mesh, computational aspects