Simulation of stochastic pressure loads on a medium head Francis runner

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Abstract. In recent years, major advances have been made in simulating dynamic and transient flows in hydraulic turbines. Overall, computational fluid dynamics (CFD) and finite element analysis (FEA) simulations have been quite successful and have helped to advance knowledge beyond the best efficiency point. The simulation of transient operations like startup and runaway has nearly become part of the standard toolbox. However, numerically predicting stochastic flows, such as those occurring during speed-no-load (SNL) regime, remains a challenge. Since these flows can have a significant impact on turbines’ life expectancy, CFD methods need to be improved. In this paper, we examine the SNL regime in a Francis turbine in which extensive dynamic fluctuations were measured. The approach used was to first focus on the CFD methodology required to better predict stochastic pressure loads with hybrid turbulence models such as the Scale-Adaptive Simulation–Shear-Stress Transport (SAS-SST) model and the relatively new Stress-Blended Eddy Simulation (SBES) model. This will then allow us to determine the amount of LES content required to accurately predict large-scale turbulent structures and the corresponding pressure fluctuations that they generate on blades.

1. Introduction

Although major progress has been made in dynamic and transient computational fluid dynamics (CFD) simulations involving hydraulic turbines, many limitations remain, notably in incorporating the roles of cavitation, air injection and certain fluid-structure interaction (FSI) phenomena in the prediction of stochastic flows often encountered in the speed-no-load (SNL) regime. This flow condition is characterized by disorganization and randomness, which are required to fully dissipate the head. Many recirculation and eddy structures are present, interacting with one another and resulting in a highly dynamic regime that generates substantial losses. This type of flow requires the simulation of a much broader turbulent spectrum than is usually required for hydraulic turbines.

In this paper, some preliminary work on SNL simulations is presented in order to determine the appropriate CFD approach for a single application case study. It is part of a much larger project to predict the life expectancy of individual hydraulic turbines based on their actual use. The aim of the project is to establish the risks and operating costs associated with each regime, in order to optimize asset management, operation and maintenance, so that the overall ownership costs of our turbines can be reduced. Characterizing the SNL regime is challenging, considering it can be very damaging in some turbines but quite harmless in others. Consequently, a fairly large dataset must be evaluated in order to determine a statistically significant approach. As previously stated, this study focused on a
single turbine, serving as a starting point for a broader study involving more units. This specific turbine was chosen because of the extensive stochastic loads found during a recent measurement campaign. This provided an opportunity to revisit SNL simulations we conducted a few years ago in our first attempt on the subject [5] and to re-evaluate our capacity to model stochastic flow with sufficient accuracy. It has allowed us to benefit from recent advances in computational power and in turbulence modelling, focusing on the recently introduced Stress-Blended Eddy Simulation (SBES) model. The next step will be to generalize the approach in order to gain confidence in the capacity of CFD as a prediction tool, while moving on to FSI simulation and reliability predictions.

2. Experimental results
A medium head Francis turbine recently refurbished by Hydro-Québec was extensively instrumented shortly after commissioning. Strain gauges (SG) were installed in a rosette configuration on two runner blades, at a number of critical locations based on the expected hotspots; pressure sensors were also installed in the penstock, spiral casing and draft tube. Other data such as guide vane opening angle, power, rotating speed, vibrations and flow rate were also measured. One specific goal of this campaign was to optimize the startup sequence. Although this paper will focus on the fluid aspects, turbine behaviour is represented from the strains perspective (based on the available data). Therefore, a strong link between loads and the resulting strains is assumed. Among the various SGs, only the one showing the greatest fluctuations, located near the trailing edge (TE) of a blade near the band, will be presented.

The maximum principal stress recorded over time is shown in Figure 1a for a 20-rotation sample under SNL. Results are normalized by static stress at maximal opening. As the figure shows, the observed dynamic content corresponds to roughly 20–30% of the static stress at full load. Furthermore, the fluctuations display no regular or predictable patterns. In addition, the synchronous average extracted from this signal is plotted in red to highlight the fact that dynamic fluctuations are an order of magnitude greater than average fluctuations. To provide an alternative view of the stochastic content, a Fast-Fourier Transform (FFT) of the residual signal (the original signal minus the synchronous average) is also plotted (Figure 1b). The most energetic fluctuations result from low-frequency content, even though fluctuations with relevant energetic content occur over a broad range of frequencies. The blade-passing frequency (20 times the rotation) is not observed in the results for this turbine. Four rainflow analyses of the signal are also plotted against each other (Figure 1c): the red curve with the smaller amplitudes corresponds to the synchronous average and shows the cycle count for one average runner rotation, with the counts for 1, 50 and 250 rotations also shown. Statistical convergence is not reached even for high range/low frequency cycles.

![Figure 1](image)

**Figure 1.** (a) Temporal maximum principal stress signal for a 20-rotation sample at the TE SG; (b) FFT of residual signal; and (c) rainflow counts for different rotation samples

1 This turbulence model developed by ANSYS is described as an LES model that switches efficiently between the Reynolds-averaged Navier–Stokes (RANS) and LES zones. [1]
2 While not shown here, the results vary from one blade to another as well for the same SG. This still holds true when comparing 250 runner rotations.
3. Numerical setup

CFD simulations were performed using ANSYS CFX 19.2 to characterize the SNL flow for this turbine and predict stochastic pressure loads. The setup, shown in Figure 2, includes the complete runner (13 blades) and distributor (20 stay vanes and guide vanes) as well as the entire draft tube. The spiral casing was omitted from the simulations since the small guide vane opening angle was expected to act as a filter to prevent major unbalances. This omission also allowed the mesh in the runner itself to be more strategically refined. High-quality, fully hexahedral meshes for the blade passages were generated with NUMECA AutoGrid5 13.1, while the mesh for the draft tube was generated with ANSYS ICEM CFD. Two mesh configurations were used: mesh1, which consisted of 21.6 million elements, including 9.1 million for the guide vane and 6.3 million for the runner (a zoom view of the mesh around the guide vane opening is shown in Figure 2) and mesh2, which consisted of 29.6 million elements in total, providing additional refinement mostly downstream of the guide vanes and throughout the runner.

![Figure 2. Simulation setup and zoom view of the distributor under SNL operating condition, showing mesh1](image)

All the simulations were conducted using a second-order upwind discretization scheme and a second-order Backward Euler time-stepping scheme. A high-resolution scheme was used for the turbulence equations. Since hybrid turbulence models were employed, the Large Eddy Simulation (LES) content was resolved with a second-order-centered scheme, which is less diffusive than the scheme used for the Reynolds-averaged Navier–Stokes (RANS) portion of the flow. Boundary conditions were the same in all simulations. A fixed value for total pressure at the inlet was used to prescribe the net head, in combination with “opening” with entrainment and average static pressure at the outlet. The rotational speed and guide vane opening angle were also constant. Transient rotor stator interfaces were used between the fixed and moving components. Wall functions were employed for the solid boundaries, with roughness specified using standard values based on the different materials involved, in order to better model losses. Water was considered incompressible. Lastly, initial conditions are provided with a steady-state RANS SST-k-Ω employing frozen rotor interfaces. Calculations were then performed for 25 rotations. The overall cost of each simulation was equivalent to roughly one week of calculations using ~700 CPUs.

4. Results

As previously mentioned, the purpose of the simulations was to determine how much stochasticity resulting from this flow condition can be captured numerically. The focus is on the greatest pressure fluctuations, which are largely responsible for the fatigue degradation mechanism. Obviously, overall quantities like flow rate and losses must be adequately predicted for this to be achieved.
First, the SBES model consistently overestimates the flow rate by as much as 30% compared to actual measurements (acoustic flowmeter). To put this in perspective, the SNL experimental flow rate corresponds to 9% of the nominal flow rate, while current simulations predict roughly 11–12%. This also means that losses are underestimated. Under SNL conditions, a small amount of torque is required to overcome the bearing and generator losses. Although the resistive torque should correspond to around 1% of the power at full load, the model predicts around 3%. To ensure that stochastic fluctuations could be judged relevant with an overestimated flow rate, a simulation was conducted using the correct prescribed flow rate. It showed that, even with a much lower net head (-30%), dynamic torque and pressure fluctuations are about the same.

In previous papers ([1][3][5]), similar flows were simulated using a Scale-Adaptive Simulation–Shear-Stress Transport (SAS-SST) turbulence model, primarily because it provided the most dynamic content for the meshes that the authors could afford. It was used again here as a reference since it provides much more content than Unsteady Reynolds-averaged Navier–Stokes (URANS) models (not shown). Figure 3 illustrates the dynamic torque on one blade for 15 runner rotations simulated with SAS-SST, using mesh1. Calculations were then performed with a SBES turbulence model, using the same mesh and the same timestep (0.5° rotation per timestep, which corresponds to an RMS Courant number of around 2.6), resulting in much greater normalized torque fluctuations. In terms of the peak-to-peak order of magnitude, fluctuations were around 20% with SAS-SST, but reached almost 30% with SBES. This ~30% value is similar to the bulk of the dynamic stress shown in Figure 1. Figure 3 provides an overview of this dynamic. The right-hand graph illustrates the dynamic torque on each blade according to the SBES simulation using mesh1: as the graph shows, each blade experiences a markedly different load over time even though the geometry is identical in all modelled sectors. The SBES model indeed shows promise in capturing flow features originating from the turbulence itself—although this was to be expected, since SBES model is supposed to act mainly as an LES model.

Figure 3. Dynamic torque over time on one blade according to three different simulations (left) and individual torque on all 13 blades according to the SBES simulation using mesh1 (right)

The results of a second SBES simulation using the much finer mesh2 are also shown. Although some slight differences can be observed, the order of magnitude is roughly the same. The finer mesh should result in the resolution of more scales, but does not really add frequency content to the torque signal; instead, it just adds somewhat greater amplitude. A finer timestep (0.25° rotation per timestep) was also simulated (not shown) but did not reveal more content in the torque signal. Although switching from a typical URANS model like k-Ω SST to a hybrid model like SAS-SST is known to generate more dynamic content, the SBES turbulence model also seems to provide significant gains when stochastic flows are expected.

Figure 4 and Figure 5 show what happens with a switch from the SAS-SST to the SBES model, comparing the instantaneous flow after 10 runner rotations with SAS-SST to the flow resolved with
SBES after three additional runner rotations. Turbulent viscosity decreased dramatically from one model to the other (as can be seen in Figure 4). This allows a broader spectrum of turbulence structures to exist simultaneously in the flow, as can be seen in Figure 5. Flow at the entrance to the runner is much less coherent with the SBES model than the SAS-SST model, which probably partially explains the difference in fluctuations. In both cases, the streamlines show how disorganized the flow is when it enters the draft tube, where a significant portion of the losses occur.

![Streamlines and vortical structures](image)

**Figure 4.** Instantaneous turbulent viscosity ratio obtained with the SAS-SST (after 10 runner rotations) and SBES (after 13 rotations) models

Although pressure sensors were not installed on the blades during the measurements, this information can be easily obtained through the simulations. Looking at two pressure sensors located at the SG location (at the leading [LE] and trailing edges [TE] near the band), detailed characteristics on a more local scale of the flow can be inferred. Figure 6 shows the temporal signal obtained with the SBES model (mesh1), the resulting FFT output and rainflow counts for both pressure sensors.

![Pressure sensors](image)

**Figure 5.** Streamlines and vortical structures illustrated with Q-criterion, colored with pressure level, obtained with SAS-SST (after 10 rotations) and SBES (after 13 rotations) models

![Pressure data](image)

**Figure 6.** Temporal signal obtained with the SBES model (mesh1), the resulting FFT output and rainflow counts for both pressure sensors.
Although the signal is short in duration (10 rotations), it nevertheless demonstrates that the stochastic content of the large structures in the flow can be captured. This translates into major fluctuations at both locations, contrary to what was observed during SNL at the end of a startup using the SAS-SST model [4]. The blade-passing frequency at the LE can clearly be seen but is completely absent at the TE. At the second location, the pressure signal seems to originate mainly from the local flow features.

5. Conclusion
In conclusion, given the major gaps that remain in our understanding of stochastic flows in hydraulic turbines and the fact that these flows can be damaging to some runners, we decided to investigate a variety of turbines operating under SNL conditions, beginning with the one in this study. This case is particularly interesting due to the large fluctuations measured. Flows were simulated using two hybrid turbulence models: the now well-established SAS-SST model as well as the recently introduced SBES model. Even though losses were underestimated by both models, the results show that significant stochastic content can be reproduced numerically. We observed that, at an equivalent cost, SBES allows more fluctuations to be simulated than SAS-SST, perhaps paving the way for affordable industrial-scale LES in the future. In this study, additional spatial and temporal refinements did not result in significant improvements. This could mean that the relevant dominant large-scale low-frequency phenomena have already been captured. A number of questions need to be answered in the future. The most important one is: To what extent can CFD predict the stochastic nature of the flow? How realistic is the stochastic content? Do the large-scale structures captured by the SBES model correspond to what occurs in a real machine? When combined with a statistical approach, does the model generate realistic enough low-frequency content to predict large-scale cycles? To draw more universal conclusions about stochastic load prediction using the current approach, other turbines operating under a SNL regime will need to be investigated. FSI will also be required to ensure that stochastic loads translate into stochastic stresses and to compare them with measurements.

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