Scale Adaptative Simulation of the Turbulent Flow at the Wicket Gate of a Kaplan Turbine

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Abstract
This paper presents results of an unsteady numerical simulation of the turbulent flow through the wicket gate of a Kaplan Turbine using the SAS SST model in normal and partial operation conditions. Its domain belongs to a Kaplan Turbine installed at CoaracyNunes plant, located north of the Brazilian amazon. The flow through the wicket gate can generate dynamic loads that might cause mechanical failures at the mechanical system that hold the guide vanes. Therefore, knowledge of this flow and its mechanical effects on the vanes is necessary to assess the possibility of failures. The parallelized version of ANSYS CFX 11 commercial code will be employed to conduct the simulation. Results of streamlines, average torque and maximum torque variation will be showed. The obtained torque signals from four vanes of the wicket gate will be shown and used to calculate its spectra. The obtained results showed that one of the vanes received high and cyclical torque variation, which can be seen on its spectrum.

Keywords: Spiral casing, Kaplan Turbines, SAS, turbulence, torque signal.

1. INTRODUCTION
The flow inside a spiral casing and within the wicket gate holds great complexity due to the inner nature of the turbulent flow and the appearance of dynamical stresses over its mechanical parts (Balint et al. (2002), Biswas et al. (2004)). Those stresses are, in a great part, originated by a complex 3D turbulent flow topology that interacts with the mechanical parts of the turbine, in particular with the wicket gate. Some of its
structural stresses are taken into account for the project and design of the gate. Therefore, advanced methodologies of analysis for mechanical and fluid simulation must be employed for this situation, since those two problems influence each other. This is an area known as fluid-structure interaction, where knowledge on fluid mechanics, solid mechanics and vibrations are needed. A great number of vibrations problems in turbomachinery have hydrodynamic origins, such as pressure oscillations and cavitation (Ciocan et al. (2000)). Effects of fluid-structure interaction and the stresses originated by this interaction induce cumulative damage and mechanical failures at those parts due to cyclical stresses. Those pathologies can force an approximately 10-day halt at the turbine operation for maintenance.

The flow inside the spiral casing involves the water inlet from the dam, through the outlet located at the entrance of the runner. In a normal load condition (where the turbine operates on its maximum efficiency point) it is expected that the attack angle of the guide vanes will induce a steady, perturbation-free flow, which maximizes the energy production. On this condition, the flow will induce a torque over the vanes, which originates loads at the crank-connecting rod system connected to the vanes and its locking pins. Also, vortex shedding and boundary layer separation influences those loads too. Those effects are a consequence of an unsteady flow behavior at the wicket gate.

The present work will study the spiral casing of a 25 MW Kaplan turbine, mounted at the CuaracyNunes hydro power plant in conditions of normal and partial operation. This turbine is showed at figure 1. Those conditions are determined by the inlet flow rate. Results of a transient numerical simulation conducted by ANSYS CFX commercial code with the SAS SST turbulence model will be presented, as well as average torque and its maximum variation at the vanes for both conditions. Also, torque signals on four of the vanes and its spectra will be shown. The following sections will present the mathematical formulation of the SAS SST model, the used boundary conditions, qualitative and quantitative results and its conclusions.

Figure 1: Kaplan Turbine

2. MATHEMATICAL FORMULATION
In a framework for turbulence modeling, for incompressible turbulent flows, the conservation of mass and momentum can be expressed by the classical Reynolds averaged equations given by (Menter and Egorov (2005)):

\[
\frac{\partial u_i}{\partial x_i} = 0
\] (1)
\[
\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} \left[ (v + \nu_T) \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right]
\] (2)

In those equations \(u_i\) and \(p\) are the mean velocity and pressure fields, \(v\) and \(\nu_T\) are the kinematic and turbulent viscosity, respectively, and \(\rho\) is the fluid density.

Menter (Menter et al., 2003) created the SST model, and its principle lies on blending the \(k-\varepsilon\) and the \(k-\omega\) model. Far from the wall, the model uses the \(k-\varepsilon\) formulation, and near the wall, the model uses the \(k-\omega\) model. The Scale Adaptative Simulation is a concept based on giving LES behavior in detached flow regions. Using equilibrium assumptions, a standard \(k-\varepsilon\) model is transformed into a one equation model, where the Von Karman length scale appears at the sink term. According to the authors, this term is responsible to provide dynamical behavior to the model. The model adjusts the resolved scales, developing an energy cascade present in separated turbulent models. The transport equations for the SST model are:

\[
\frac{\partial k}{\partial t} + u_j \frac{\partial k}{\partial x_j} = P_k - \beta \kappa \omega + \frac{\partial}{\partial x_i} \left[ \left( \frac{v + \nu_T}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right]
\] (3)

\[
\frac{\partial \omega}{\partial t} + u_j \frac{\partial \omega}{\partial x_j} = \alpha \rho S^2 - \beta \rho \omega + \frac{\partial}{\partial x_i} \left[ \left( \frac{v + \nu_T}{\sigma_\omega} \right) \frac{\partial \omega}{\partial x_i} \right] + 2(1 - F_1) \sigma_{\omega^2}
\] (4)

Here, \(k\) and \(\omega\) are the turbulent kinetic energy and turbulent frequency. The eddy viscosity is defined by:

\[
\nu_T = \frac{\alpha_1 k}{\max \left( \alpha_1 \omega, (S_{ij} S_{ij})^{0.5} F_2 \right)}
\] (5)

Where \(S\) is an invariant measure of the tensor rate and \(F_2\) is one of two blending functions of the model. The formulation of the blending functions \(F_1\) and \(F_2\) are based on the distance from the surface and on the flow's variables. The blending functions \(F_1\) and \(F_2\) are given as follows:

\[
F_1 = \tanh (\text{arg}^4_1)
\] (6)

\[
\text{arg}_1 = \min \left[ \frac{\sqrt{k}}{\beta \omega}, \frac{500 \nu}{\gamma^2 \omega}, \frac{4 \sigma_{\omega^2} k}{CD_{k\omega}}, \frac{1}{\omega} \nabla k \nabla \omega, 10^{-10} \right]
\] (7)

\[
CD_{k\omega} = \max \left( 2 \rho \sigma_{\omega^2} \frac{1}{\omega} \nabla k \nabla \omega, 10^{-10} \right)
\] (8)

Here, \(y\) is the distance to the wall. \(F_1\) is equal to zero away from the surface (\(k-\varepsilon\) model) and switch over to 1 inside the boundary layer (\(k-\omega\) model). \(F_2\) is given by:

\[
F_2 = \tanh (\text{arg}^2_2)
\] (9)

\[
\text{arg}_2 = \max \left( \frac{2 \sqrt{k}}{\beta \omega y}, \frac{500 \nu}{\gamma^2 \omega} \right)
\] (10)
The blending function $F_2$ restrains the limitator for the boundary layer wall. A production limiter is used to avoid the growth of turbulence in stagnation regions:

$$P_k = \mu \frac{\partial u_i}{\partial x_j} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

$$\overline{P_k} = \max(P_k, 10\rho \beta^* k\omega)$$

The model's constants are accounted by a blend of the corresponding constants of the $k$-$\varepsilon$ and the $k$-$\omega$ models with the following function:

$$\alpha = \alpha_1 F_1 + \alpha_2 (1 - F_1) + \cdots$$

The constants are $\beta=0.09$, $\alpha_1=5/9$, $\beta_1=3/40$, $\alpha_{\omega l}=0.5$, $\sigma_{\omega l}=0.5$, $\alpha_2=0.44$, $\beta_2=0.0828$, $\sigma_{\omega 2}=1$, $\sigma_{\omega 2}=0.856$.

The analytical expression for $\omega$ provided by $\omega$-equation turbulence models allows a near-wall formulation, which gradually switches from wall-functions to low Reynolds near wall formulations when one goes far from the wall.

The $\omega$-equation transformed for the SAS model is (Menter and Egorov (2005)):

$$\frac{\partial \omega}{\partial t} + u_j \frac{\partial \omega}{\partial x_j} = \alpha \rho S^2 - \beta \rho \omega^2 + \frac{\partial}{\partial x_i} \left[ \left( \frac{\nu_T}{\sigma_{\omega l}} \right) \frac{\partial \omega}{\partial x_i} \right] + \frac{2\rho}{\sigma_{\phi}} \left( \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i} - \frac{k}{\omega^2} \frac{\partial \omega}{\partial x_i} \frac{\partial \omega}{\partial x_i} \right)$$

$$+ \xi^2 k \rho S^2 \frac{L}{L_{vk}} + \frac{\rho \omega}{\kappa \rho} \frac{\partial}{\partial x_i} \left( \frac{\mu_x}{\rho \sigma_{\phi} \partial x_i} \left( \frac{1}{\sigma_k} - \frac{1}{\sigma_{\phi}} \right) + F_{SAS-SST} \right)$$

The Von Kármán length scale is given as follows:

$$L_{vk} = \kappa \left( \frac{\partial u_i / \partial x_i}{\partial^2 u_i / \partial x_i^2} \right)$$

To preserve the SST model in the RANS portion of the flow and SAS model in the URANS portion, the following condition must be fulfilled:

- For the RANS regime:

$$\frac{2\rho}{\sigma_{\phi}} \frac{k}{\omega^2} \frac{\partial \omega}{\partial x_i} \frac{\partial \omega}{\partial x_i} \approx \xi^2 k \rho S^2 \frac{L}{L_{vk}}$$

- For the SAS regime:

$$\frac{2\rho}{\sigma_{\phi}} \frac{k}{\omega^2} \frac{\partial \omega}{\partial x_i} \frac{\partial \omega}{\partial x_i} < \xi^2 k \rho S^2 \frac{L}{L_{vk}}$$

Where ($C_{\mu}=0.09$ and $\kappa=0.41$):

$$L = \frac{\sqrt{k}}{C_{\mu}^{0.25}} \omega$$

130
The blending function for the SAS model is given as follows:

\[
F_{\text{SAS-SST}} = \rho F_{\text{SAS}} \max \left[ \zeta^2 \kappa \rho S^2 \frac{L}{L_{vk}} - \frac{2}{\sigma_\Phi} \max \left( \frac{1}{\omega} \frac{\partial \omega}{\partial x_i}, \frac{1}{\kappa} \frac{\partial \kappa}{\partial x_i} \right), 0 \right]
\]  

The remaining constants are given as: \( F_{\text{SAS}}=1.25, \zeta_2=1.755, \sigma_\Phi=2/3 \). One of the main setbacks of LES is its cost. This methodology demands a fine mesh and sufficient simulation time to resolve all flow scales, which makes LES an expensive alternative for complex geometries. On the other hand, DES original concept is to restrain LES calculations to detached flow regions, while offer RANS advantages in near wall regions. This trend is justified by the fact that the calculation of a separated region is less expensive than a near-wall calculation in a LES context. But DES is highly dependable on the grid scale. It needs to be smaller than the turbulent length scale to provide an accurate calculation of the flow. The SAS model is, in fact a URANS model that offer LES behavior on unsteady regions. Its aim is to pose as a feasible and accurate alternative when compared with other transient turbulent modeling, such as LES or DES. The scale \( L \) have to be adequate for the flow, for good calculations, which makes this scale the main dependance of the SAS model for an accurate simulation (Menter and Egorov (2005)).

### 2.1. Discretization and Boundary Conditions

The imposed boundary conditions specify the flow rate at the inlet, which is given by the operation data. The flow rate value in normal operation is set as 143 m\(^3\)/s, and in partial operation is set as 94 m\(^3\)/s. The gate outlet is imposed with a reference pressure condition. No-slip conditions are imposed at the considered walls. The simulation was conducted in a transient mode on a cluster with the parallelized version of ANSYS CFX commercial code. The imposed simulation time step is \( 10^{-5} \) s. Pressure and torque signals were collected at the surroundings of the blades for analysis. The generated mesh for the case has 6467792 nodes and 21561890 elements. A refinement is made at the vicinity of the vanes, as well as the use of the inflated boundary at them (Figures 2 and 3).

![Figure 2: Domain Discretization– Details](image1)

![Figure 3: Domain Discretization – Details](image2)
3. RESULTS

3.1. Flow Visualizations

Figure 4 presents the flow visualizations at the gate. The flow patterns are similar for both normal and partial operations. Its main function is to uniform the flow that goes into the runner. On most of the vanes the streamlines and velocity vectors show an adequate flow, where the fixed vanes guides the flow who passes smoothly through the guide vanes. However, one can note the presence of low pressure zones at the wake of some fixed vanes, as highlighted in blue zones at figure 4. Those low pressure zones affect the local flow at the vicinity of the guide vanes. This feature doesn't cause major influence on the global flow, where it is perfectly distributed at the runner inlet. This distribution indicates a good vane positioning in both conditions. It is noted that the recirculation originated by the fixed vanes varies with time, which modifies the flow over the guide vane. The streamlines shows a symmetric flow after the vanes and through the runner inlet, which is main goal of the casing.

![Figure 4: 3D Streamlines and Pressure Contour at a fixed vane](image)

3.2. Torques at the Vanes

Figure 5 shows the numbering and position of each guide vane, and table 1 shows the average torque for both normal and partial conditions. Also, the table shows the maximum variation for both conditions. At the normal condition results, one can observe that the average torques is in the same order of magnitude, except for vane 11. On this vane, the average torque is ten times smaller than the other vanes. Also, it is noted that vane 4 has a negative signal. This signal indicates that the flow induces an opening tendency on the wicket gate through that vane. Vanes 1 from 8 and 15 shows torque maximum variations below 100 N.m, and the remaining vanes showed variation above this value. Vane 11, while it has a lower average torque value, has the highest torque maximum variation. For the results in partial load condition, vane 13 shows average torque values ten times smaller than the other vanes. Negative torque values are noted at vanes 4 and 11, inducing also an opening tendency on the wicket gate through those vanes. The maximum torque variation values show no significant variations between the vanes when compared with the normal condition. All the variations are between 5 and 20 N.m.

One can note that vane 11, in both conditions, shows the most significant torque variations. Also, vanes 1, 8 and 13 showed the biggest values of maximum torque variation. The observed values, induced in a periodic manner, can induce mechanical failure and fracture at the mechanical systems of the turbine. Therefore, a more profound analysis will be made on those vanes at the next section.
Table 1: Average and Maximum Torque Values

<table>
<thead>
<tr>
<th>Vane</th>
<th>Normal Condition</th>
<th>Partial Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Torque</td>
<td>Maximum Variation</td>
</tr>
<tr>
<td>1</td>
<td>7199.7</td>
<td>91.2</td>
</tr>
<tr>
<td>2</td>
<td>6331.6</td>
<td>46.1</td>
</tr>
<tr>
<td>3</td>
<td>2957.2</td>
<td>39.4</td>
</tr>
<tr>
<td>4</td>
<td>-8299.0</td>
<td>67.2</td>
</tr>
<tr>
<td>5</td>
<td>3185.4</td>
<td>23.2</td>
</tr>
<tr>
<td>6</td>
<td>5967.1</td>
<td>37.7</td>
</tr>
<tr>
<td>7</td>
<td>5032.5</td>
<td>24.0</td>
</tr>
<tr>
<td>8</td>
<td>4540.1</td>
<td>79.8</td>
</tr>
<tr>
<td>9</td>
<td>1706.2</td>
<td>487.0</td>
</tr>
<tr>
<td>10</td>
<td>3757.0</td>
<td>267.4</td>
</tr>
<tr>
<td>11</td>
<td>287.1</td>
<td>654.5</td>
</tr>
<tr>
<td>12</td>
<td>4526.7</td>
<td>348.3</td>
</tr>
<tr>
<td>13</td>
<td>1846.7</td>
<td>536.5</td>
</tr>
<tr>
<td>14</td>
<td>4974.9</td>
<td>259.0</td>
</tr>
<tr>
<td>15</td>
<td>3133.8</td>
<td>94.4</td>
</tr>
<tr>
<td>16</td>
<td>5330.9</td>
<td>170.1</td>
</tr>
<tr>
<td>17</td>
<td>4381.8</td>
<td>247.0</td>
</tr>
<tr>
<td>18</td>
<td>6139.9</td>
<td>221.3</td>
</tr>
<tr>
<td>19</td>
<td>5271.0</td>
<td>273.6</td>
</tr>
<tr>
<td>20</td>
<td>6632.6</td>
<td>156.7</td>
</tr>
</tbody>
</table>

3.3. Torque Signals

Figures 6 and 7 shows torque signals varying with time for vanes 1, 8, 11 and 13. Those same figures show also the spectra for the same vanes. It is noted that vanes 1 and 8 shows in their signals the absence of a periodic behavior. Their behavior is characterized by a more erratic torque signal, without any coherent pattern. This pattern is confirmed by its spectra, where no peaks are observed in any frequency bandwidth. On the other hand, vanes 11 and 13 show a periodic behavior on its signal. Their spectra show peaks at a
frequency bandwidth between $10^{-1}$ and $10^{-2}$. This result means that, at that frequency, a periodical torque oscillation is occurring. As a consequence of that, those vanes are receiving cyclical loads from the flow. The hydrodynamic visualization hasn't shown any vortex shedding, but vane 11 showed variation at its flow topology due to recirculation zones at the fixed vanes. This is an indication of transient flow phenomena at those vanes within the wicket gate. Therefore, a better grid adjustment or an adjustment of the SAS model might be required for better visualization of the flow topology that is causing the periodic oscillation of the torque.

![Figure 6: Torque Signal and Spectra at Vanes 1 and 8](image)

![Figure 7: Torque Signal and Spectra at Vanes 11 and 13](image)

4. CONCLUSIONS
Results of a numerical simulation inside a spiral casing of a Kaplan turbine were presented. Flow visualizations, as well as torque values and signals and its spectra were showed.

The effects of the flow direction by the guide vanes were observed, as well as the uniform distribution of the flow. Some fixed vanes showed recirculation zones. The torque signals indicate a periodical variation of the flow. This trend is confirmed by the torque spectra, that showed peaks at a frequency between $10^{-1}$ and $10^{-2}$. This result shows an oscillatory pattern of the torque in a couple of vanes. This oscillatory pattern indicates cyclical loads at the vanes. Those loads can cause mechanical failures at the crank-connecting rod system that holds the guide vanes.

Therefore, one can conclude that the hydrodynamic characteristics of the flow at the spiral casing ensure project conditions for homogeneous flow at the runner inlet. But the fixed vanes generate low-pressure zones that can induce cyclical on some of the guide vanes, noted by the torque signals. In order to pinpoint the origin of that phenomenon, further simulations must be conducted.
5. ACKNOWLEDGMENTS
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6. REFERENCES


