Large Eddy Simulations on Vertical Axis Hydrokinetic Turbines and flow phenomena analysis

N Guillaud1, G Balarac1, E Goncalvès2 and J Zanette3

1 Grenoble-INP/CNRS/UJF-Grenoble 1, LEGI UMR 5519, 1209-1211 rue de la piscine, Domaine Universitaire, 38400 Saint Martin d’Hères, France
2 ISAE-ENSMA/CNRS, Pprime UPR 3346, SP2MI - Téléport 2 11 Boulevard Marie et Pierre Curie, BP 30179 86962 Futuroscope Chasseneuil Cedex, France
3 Hydroquest SAS, Le Tarmac, 29 chemin du Vieux Chene, 38240 Meylan, France

E-mail: Nathanael.Guillaud@legi.grenoble-inp.fr

Abstract.

Large Eddy Simulations have been performed on a Vertical Axis Hydrokinetic Turbine (VAHT) at various tip speed ratios. The turbine power coefficient and the flow through the turbine show good agreement with experimental data. To better understand the evolution of the VAHT power coefficient through the tip speed ratios the contribution of the VAHT main regions to the global power coefficient has been evaluated. At the optimal tip speed ratio ($\lambda = 2$) blade tip vortex and blade/arm connection drag generate losses and decrease the efficiency of the regions around the blade tip and blade/arm connection. The region around the blade tip is the most degraded. When the tip speed ratio decreases to $\lambda = 1$, deep dynamic stall with the presence of a Leading Edge Vortex is observed at early angular positions and leads to the power coefficient drop. The power coefficient drop around the blade tip and the blade/arm connection happens at higher angular position than on the middle part of the blade. For a tip speed ratio higher than optimal, the region around the blade/arm connection shows the highest decrease in efficiency. Despite its small height compared to the blade this region is responsible for about 36% of the VAHT power coefficient decrease at $\lambda = 2.5$.

1. Introduction

Tidal currents represent a large renewable energy resource concentrated in a few dozen sites in the world [1]. Vertical Axis Hydrokinetic Turbines (VAHT) have less impact on the environment and are less expensive than traditional hydropower facilities. They are also faster to install and allow the exploitation of more sites due to their flexibility to create large arrays of turbines within regions such as rivers, man-made channels or tidal straits where the local bathymetry focuses the flow [2]. Given the promise of VAHT technology the investigation of their performance is of increasing interest to researchers. The VAHT type studied here is an Achard turbine [3]. The performance depends on the operating condition of the blade, blade tip vortices and blade/arm connection losses [4]. The importance of each of these phenomena depends on the operating conditions and the geometry considered. The analysis of these phenomena and their respective roles are of paramount importance to improve the turbine performance, but they are challenging to predict. According to [4], 2D and 3D URANS type simulations are able to approximate the turbine performance but overestimate it. LES have been performed here to improve the accuracy of the results with an explicit description of a larger part of the turbulent phenomena.
Due to the rotation of the turbine, the relative velocity $\vec{W}$ at an arbitrary point $M$ is equal to $V_0 - \vec{\Omega} \times \vec{OM}$, where $V_0$ is the free-stream velocity, $\vec{\Omega}$ the rotation speed, $O$ the intersection point between the VAHT symmetry plane and the VAHT rotation axis. As described in [4], the relative velocity magnitude $W$ and the associated incidence $\alpha$ on a VAHT blade can be expressed as:

$$W = V_0 \sqrt{1 + 2 \lambda \cos(\theta) + \lambda^2}$$  \hspace{1cm} (1)$$

$$\alpha = \arctan \left( \frac{\sin(\theta)}{\cos(\theta) + \lambda} \right)$$  \hspace{1cm} (2)$$

where $\theta$ is the angular position of the VAHT defined on figure 2 and $\lambda$ the tip speed ratio. The tip speed ratio is equal to $\frac{\Omega R}{V_0}$, where $\Omega$ is the turbine rotation speed magnitude and $R$ the turbine radius. The relative velocity magnitude and the VAHT blade incidence evolution through the angular positions are represented on figure 3. The blade incidence is thus time dependant and periodic. A reduced frequency for VAHT is given by [5]:

$$k = \frac{c}{\Omega R} \frac{\dot{\alpha}_{\text{max}}}{2 \alpha_{\text{max}}} = \frac{c}{R} \frac{1}{\lambda - 1} \frac{1}{2} \left( \arctan \left( \frac{1}{\sqrt{\lambda^2 - 1}} \right) \right)^{-1}$$  \hspace{1cm} (3)$$

The lower the tip speed ratio, the higher the VAHT reduced frequency which can lead to the dynamic stall phenomenon [6]. According to [7], if the tip speed ratio is too low early deep dynamic stall phenomenon occurs and decreases the turbine efficiency. A high tip speed ratio leads to increase losses. There is an optimal tip speed ratio between these two cases where these phenomena are balanced and lead to the best turbine performance. The flow through the turbine and the associated turbine efficiency are thus significantly controlled by the tip speed ratio. The aim of the present study is to better understand the role of the phenomena impacting the turbine efficiency and their evolution through the tip speed ratios.

2. Study cases and numerical set up
The geometry used for the LES is a scale model represented on figure 1, and its characteristics are summarized in table 1. The free-stream velocity $V_0$ is set to 2.8 m/s. Three tip speed ratios are studied: $\lambda = 2$, which is the best efficiency operating point, $\lambda = 1$ and $\lambda = 2.5$.

The mesh for the LES contains approximately 105 million cells. The most likely value of first cell size equals to 3 wall unit along the turbine and is always smaller than 20 wall unit in all tested
Figure 3: Theoretical relative velocity for $V_0 = 2.8m/s$ (a) and incidence on the blade (b) across a VAHT revolution for different tip speed ratios.

Table 1: Scale model geometry characteristics

| Parameter              | Value   | Parameter              | Value   |
|------------------------|---------|------------------------|---------|
| Blade number           | 3       | Radius $R$             | 87.5mm  |
| Blade geometry         | projected NACA, half-chord tangent | Blade solidity $\frac{c}{R}$ | 0.37    |
| Chord $c$              | 32.1mm  | Height $H$             | 175mm   |

Tip speed ratios. Computations were performed using the YALES2 flow solver [8]. This code solves the incompressible and low-Mach number Navier-Stokes equations for turbulent flows on unstructured meshes using a projection method for pressure-velocity coupling [9]. It relies on fourth-order central finite-volume schemes and on highly efficient linear solvers [10], which enable the simulation and the post-processing of iso-thermal, reacting or multiphase flows on massive unstructured grids [11–13]. The Smagorinsky dynamic subgrid-scale model is used [14]. To avoid rotor/stator interface, equations are expressed in a rotating frame and a rotating velocity condition is imposed at the inlet. The domain extension is equal to $16D$ around the hydrokinetic turbine and $1.43H$ in the spanwise direction where symmetry boundary conditions are imposed.

3. LES validation

The turbine performance is evaluated with the power coefficient $C_{p}^{VAHT}$:

$$C_{p}^{VAHT} = \int_{S_{VAHT}} C_{p} \left(\overrightarrow{OM}\right) dS$$

(4)

where $S_{VAHT}$ is the turbine surface. $C_{p} \left(\overrightarrow{OM}\right)$ is defined as:

$$C_{p} \left(\overrightarrow{OM}\right) = \lambda \left(\overrightarrow{OM} \wedge \left(-\overrightarrow{Pn} + \overrightarrow{\bar{v}} \cdot \overrightarrow{n}\right)\right) \cdot \overrightarrow{v}$$

(5)
where $\rho$ is the water density, $D$ and $R$ the turbine diameter and radius, respectively, $H$ the turbine height, $P$ the pressure, $\tau$ the viscous stress tensor, $\vec{n}$ the surface normal and $\vec{e}_z$ the axial unit vector.

To validate the LES, the obtained power coefficients are compared to those from a similar experimental configuration [15]. The horizontal blockage ratio is defined as $\epsilon = D/L$, where $L$ is the water tunnel section width. It is equal to 0.25 in the experimental case and to 0.0625 in the LES. According to [16], the flow through the turbine, and thus the turbine performance, decrease as the blockage ratio decreases. This is shown by the streamlines, which are more deviated by the VAHT when the blockage ratio decreases. Lower power coefficients are therefore expected from the LES compared to the experimental data. Figure 4 shows the evolution of the mean power coefficient during a revolution $\left(C_p^{VAHT}\right)$ as a function of tip speed ratio. The bell-shaped curve is well reproduced by the LES. When the tip speed ratio is low, the streamlines are less deviated since the flow blockage by the turbine is less important. The mean power coefficient is thus closest to the experimental data at $\lambda = 1$.

Figure 5 depicts the evolution of the instantaneous VAHT power coefficient with the angular position $\theta$. At $\lambda \geq 2$, a blade creates most of the torque in the 60-120° region. As the turbine has three equally spaced blades, the instantaneous turbine power coefficient shows three periodic areas corresponding to successive blades passing into the 45-150° region. At $\lambda = 1$, the maximum torque regions are shifted toward lower angular positions. These power coefficient evolutions are well predicted by the LES. The values of $C_p^{VAHT}$ are, as expected, lower than the experimental data and closest to them for $\lambda = 1$.

To complete the simulation validation, the flow around the blade is compared with a flow field obtained by PIV in [17] for different angular positions on figure 6. The main flow phenomena are captured, especially at $\lambda = 1$ where the so-called LEV (Leading Edge Vortex) characteristic of the deep dynamic stall [18] is observed.

![Figure 4: VAHT mean power coefficient as a function of the tip speed ratio.](image1)

![Figure 5: VAHT power coefficient as a function of the angular position.](image2)

4. Power coefficient and associated flow phenomena analysis

To analyze the turbine performance and the associated flow, the power coefficient is divided into turbine region contributions. A regional power coefficient is introduced:
The regional power coefficient is calculated on the regions defined on figure 7. Note that only the symmetry upper part of one blade is considered.

As the region heights are not equal, a region efficiency is defined as:

\[ \eta_{\text{region}} = \frac{C_{p_{\text{region}}}}{h_{\text{region}}} \]  

where \( h_{\text{region}} \) is the height of the considered region.

As the regions have been defined on the symmetry upper part of one blade, there is six occurrences of each region in the turbine. To obtain the total contribution of the six occurrences of a region to the mean turbine power coefficient, \( \left\langle C_{p_{\text{region type}}} \right\rangle \) is defined as:

\[ \left\langle C_{p_{\text{region type}}} \right\rangle = \sum_{i=1}^{6} \left\langle C_{p_{\text{region}}} \right\rangle \]  

Where \( \langle C_{p_{\text{region}}} \rangle \) is the mean region power coefficient over a revolution. The mean efficiency over a revolution of a region type \( \langle \eta_{\text{region type}} \rangle \) is defined as:

\[ \langle \eta_{\text{region type}} \rangle = \frac{\langle C_{p_{\text{region type}}} \rangle}{6h_{\text{region}}} \]  

Finally, a more local analysis will also be performed looking at the \( C_{p_{p_{\text{region}}}} \left( \bar{OM} \right) \) distribution over the VAHT surface.

The regional power coefficients on the shaft, arm/shaft connection and arms are negligible and will not be reported here. After a focus on the optimal tip speed ratio (\( \lambda = 2 \)) for the identification of the flow phenomena limiting the turbine performance, the origins of the power coefficient decrease at a lower tip speed ratio (\( \lambda = 1 \)) and at a higher tip speed ratio (\( \lambda = 2.5 \)) will be investigated.

4.1. Optimal operating condition (\( \lambda = 2 \))

The best performance tip speed ratio is first considered to highlight the flow phenomena leading to the turbine performance limitation. Figure 8a shows the evolution of \( C_{p_{\text{region}}} \) through the angular positions \( \theta \). As only one blade is considered, the major part of the power coefficient is brought into the 45-150° region. At this tip speed ratio the VAHT reduced frequency is high and the dynamic stall phenomenon allows a
high torque level to be temporarily maintained when the blade incidence goes beyond the static stall angle of incidence after $\theta \approx 60^\circ$, as shown by figure 3b. From $\theta = 100^\circ$ to $\theta = 150^\circ$, the power coefficient decreases. During the rest of the revolution the axial torque is very low and could even reach negative values. Into the 150-210° and 315-45° areas, it is due to the fact that the blade faces the flow with low incidences. Into the 210-315° area, the absolute velocity is low due to the influence of the other blades and the shaft, as illustrated by figure 9. The blade incidence and the relative velocity are strongly modified compared to the values given by equations 1 and 2 and leads to low torque values.

As shown in figure 8a most of the power coefficient is attributed to the blade region. The small height of the tip blade and blade/arm connection regions partly explains their lower contributions to the VAHT power coefficient. However, figure 8b, which depicts the region efficiency through the angular positions, shows that the blade tip and the blade/arm connection region efficiencies are also lower than that of the blade region. Figure 10b highlights a blade tip vortex, and figure 10a shows that it impacts the distribution of $C_p \left( \vec{OM} \right)$ around the blade tip and leads the blade tip region to be the least efficient part of the turbine, as shown in the table 2. Concerning the blade/arm connection region, it seems that a negative torque at its rear part is responsible for its lack of efficiency.
4.2. Low tip speed ratio operating condition ($\lambda = 1$)

The tip speed ratio $\lambda = 1$ is now considered to study the origins of the turbine performance decrease at $\lambda < \lambda_{optimal}$. At this tip speed ratio, the power coefficient on the blade region is higher than the power coefficient found at the operating condition $\lambda = 2$ until $\theta = 45^\circ$, after which it dramatically falls and becomes close to zero as shown in figure 11a. According to equation 3, the VAHT reduced frequency tends to be infinite. The dynamic stall phenomenon is deeper than at $\lambda = 2$, leading to a larger and more sudden drop in the axial torque attributed to the blade region. Figure 11b shows that the axial torques attributed to the blade tip and the blade/arm connection regions are also falling, but at a higher angular position. As in [19], the presence of a vortex on the suction side of the blade is visible on the figure 12b. This vortex is characteristic of the deep dynamic stall and is called the Leading Edge Vortex (LEV) [18].

It has been shown that this vortex generates a high lift level on the blade from the moment it is generated at the blade’s leading edge until the moment it detaches completely from the blade [20]. Evidence for the the effect of the LEV on performance is seen directly in figures 12a and 12b. For the angular position shown in these figures ($95^\circ$), the LEV is shown to be detached in the blade region, and there is a corresponding low level of $C_p\left(\tilde{OM}\right)$, but the LEV is still attached at the blade tip and blade/arm connection regions, which show a high level of $C_p\left(\tilde{OM}\right)$. Thus a high $C_{p\text{region}}$ level is observed during a larger angular position interval on the blade tip and the blade/arm connection regions compared to the blade region as shown in figures 11a and 11b. The blade region is consequently the most impacted region by this tip speed ratio change, as reported in table 3.
Figure 11: $C_p^{\text{region}}$ for blade (a), blade tip and blade/arm connection (b) regions as a function of the angular position. ——: $\lambda = 1$, —— : $\lambda = 2$, ⬤: blade, • : blade tip, ▴: blade/arm connection.

Figure 12: $C_p \langle \overline{OM} \rangle$ contour (a) and iso-surface of Q-criterion coloured by axial vorticity ($s^{-1}$) (b) along a blade at $\theta = 95^\circ$ for $\lambda = 1$.

Table 3: $\langle \eta^{\text{region type}} \rangle$ and $\langle C_p^{\text{region type}} \rangle$ for $\lambda = 1$ and the decrease compared to $\lambda = 2$

| Region                  | $\langle \eta^{\text{region type}} \rangle$ (m$^{-1}$) | $\Delta \langle \eta^{\text{region type}} \rangle$ (m$^{-1}$) | $\langle C_p^{\text{region type}} \rangle$ | $\Delta \langle C_p^{\text{region type}} \rangle / \Delta (C_p^{\text{VART}})$ (%) |
|-------------------------|------------------------------------------------------|-------------------------------------------------|------------------------------------------|----------------------------------------------------------------------------------|
| Blade                   | 0.273                                                | -0.318                                          | 0.0820                                   | 80.4                                                                             |
| Blade tip               | 0.285                                                | -0.076                                          | 0.0300                                   | 6.8                                                                              |
| Blade/arm connection    | 0.319                                                | -0.108                                          | 0.0382                                   | 10.9                                                                             |

4.3. High tip speed ratio operating condition ($\lambda = 2.5$)
The tip speed ratio $\lambda = 2.5$ is now considered to investigate the origins of the turbine performance decrease at $\lambda > \lambda_{optimal}$. As shown in figure 13, the blade region contribution to the turbine power coefficient is slightly less than that of $\lambda = 2$ for every angular position, as does the contribution of the blade/arm connection region for $100^\circ \leq \theta \leq 45^\circ$. The contribution of the blade tip region is the least impacted by this tip speed ratio change. At $\theta = 95^\circ$, it seems that the negative torque seen at $\lambda = 2$ at the blade suction rear part is amplified for $\lambda = 2.5$ as shown on figure 14. The positive torque area of
5. Conclusions
LES have been performed on a Vertical Axis Hydrokinetic Turbine (VAHT) at three different tip speed ratios in order to better understand the evolution of the VAHT power coefficient through these tip speed ratios. At the optimal tip speed ratio $\lambda = 2$ the blade tip and the blade/arm connection regions show a lack of efficiency compared to the rest of the blade. The lack of efficiency in the blade tip region is the most important and is due to the blade tip vortex. Concerning the blade/arm connection region, the lack of efficiency is due to a negative torque area at the rear of this region. When the tip speed-ratio decreases to $\lambda = 1$, an early deep dynamic stall phenomenon appears and leads to a drop in the power coefficient. It has been shown that the axial torques attributed to the blade tip and the blade/arm connection regions drop later than the rest of the blade, which leads to a smaller decrease of the mean efficiency over a revolution in the blade/arm connection region seems to increase, but this gain of power coefficient is balanced with the increase of the negative torque at the rear part of this region. Depending on the angular position, the magnitudes of these two opposite effects vary but overall leads to an efficiency loss in this region. Table 4 sum up the efficiency losses and the impact on the VAHT power coefficient. The difference between the impact of the blade region and the blade/arm connection region has strongly reduced compared to the case $\lambda = 1$. Whereas the blade was the region with the highest level of efficiency loss at $\lambda = 1$ at $\lambda = 2.5$ the blade/arm connection region is responsible for about 36% of the VAHT power coefficient decrease, despite its small height compared to the blade.
Table 4: $\langle \eta_{\text{region type}} \rangle$ and $\langle C_{p_{\text{region type}}} \rangle$ for $\lambda = 2.5$ and the decrease compared to $\lambda = 2$

| Region                        | $\langle \eta_{\text{region type}} \rangle$ ($m^{-1}$) | $\Delta \langle \eta_{\text{region type}} \rangle$ ($m^{-1}$) | $\langle C_{p_{\text{region type}}} \rangle$ | $\frac{\Delta \langle C_{p_{\text{region type}}} \rangle}{\Delta C_{p_{\text{VAHT}}}}$ (%) |
|-------------------------------|---------------------------------------------------|---------------------------------------------------|-----------------|----------------------------------|
| Blade                         | 0.482                                             | -0.109                                             | 0.1446          | 48.6                             |
| Blade tip                     | 0.282                                             | -0.080                                             | 0.0296          | 12.4                             |
| Blade/arm connection          | 0.222                                             | -0.204                                             | 0.0267          | 36.4                             |

these regions. The blade tip region efficiency is the least impacted by this tip speed ratio decrease. When the tip speed ratio increases to $\lambda = 2.5$, the blade/arm connection region is the most heavily impacted. The negative torque at its rear part becomes more important and despite the small region height compared to the blade, it is responsible for about 36% of the VAHT power coefficient decrease. The blade region efficiency decreases as well and is responsible for approximately 49% of the VAHT power coefficient decrease. The blade tip region is the least affected by the increase in tip speed ratio.

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