Calculation and simulation of a hydrokinetic turbine for electricity generation in isolated regions in the Amazon

Keywords: Hydrokinetic turbine; Blade element momentum theory; Chord distribution; Twist angle distribution; Gottingen airfoil.

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INTRODUCTION:

Hydroelectric generation technology is not totally environment friendly since the huge water reservoirs ahead of the dams generate vegetation, which later decomposes producing methane. The Amazon is characterized by its low demographic index, the absence of electricity distribution grids and lack of qualified labor. On the other hand, it has an extensive grid of fast flowing rivers adequate for hydrokinetic electricity generation. The project consists of a numerical investigation on hydrokinetic turbines for the Amazon and similar regions. A home built numerical code for the determination of geometry and performance of horizontal axis hydrokinetic turbine is developed and optimized based on the blade element momentum theory. The investigated airfoils include symmetric and non-symmetric Gottingen 410 and 420 airfoils. The effects of the chord and twist angle distributions are investigated and their effects on the hydrodynamic performance of the turbines are evaluated and discussed.

The Blade Element theory was introduced by William Froude in 1878 and consists on cutting the turbine blades into sections, called the blade elements, approximated by a planar model, in order to study turbines from a local point of view, resulting in expressions of forces as functions of flow characteristics and blade geometry. On the other hand, the Momentum theory, also known as disk actuator theory or axial momentum theory, it was introduced by William J. M. Rankine in 1865 and models the behavior of a column of fluid passing through a turbine adopting a macroscopic point of view. Finally, the Blade Element Momentum theory (BEM), which was initially introduced to study propellers, results from the combination of the two previous theories carried out in 1925 by Lock, Bateman and Townend, later formalized in its modern form by Glauert in 1926. It is used to evaluate the performance of propelling or extracting turbines, on the basis of the characteristics of the fluid flow and mechanical and geometric parameters. Therefore, the BEM model couples the momentum theory with the local events taking place at the actual blades [2].

METHODOLOGY:

A classical software used for turbine simulations is Xfoil, a subsonic airfoil development system, downloadable freely from the MIT website, used for design and analysis, consisting of menu-driven routines. It performs functions like: lift and drag predictions for an existing airfoil, for both viscous or inviscid analysis; reading and writing of polar save files and airfoil coordinates; and plotting of geometry and pressure distribution [7]. This software program was developed by MIT Professor Mark Drela in the late 1980's as a kind of MATLAB for aerodynamicists, as it wrapped established computational techniques for airfoil design in a graphical and intuitive interface. Drela describes Xfoil, and other programs that he wrote, as numerical wind tunnels, that allow somebody to find out what a wing's or airfoil's drag and lift are by computation, in a much less costy way, in terms of time and money. It can be used to design not only aircraft, but also sailboats, propeller blades and windmills [8].

The algorithm that summarizes the classical BEM model consists of eight steps, applied for each independent control volume. As each strip can be treated separately, the solution at one radius can be computed before solving for another radius. The steps are [1]:

1. Initialize a and a', typically $a = a' = 0$.

$$\phi = tan^{-1}\left(\frac{(1-a)V_0}{(1+a')\omega r}\right)$$

2. Compute the flow angle φ using:

$$\alpha = \phi - \theta$$

3. Compute the local angle of attack using:

4. Read Cl(α) and Cd(α) from a table look-up.

5. Compute the coefficients corresponding to the normal n and tangential t projections of the lift and drag to the

$$C_n = C_l cos\phi + C_d sin\phi$$

$$C_t = C_l sin\phi - C_d cos\phi$$

rotor plane:

$$a = \frac{1}{\frac{8\pi r \cdot sin^2\phi}{c(r) \cdot B \cdot C_n} + 1}$$

$$a' = \frac{1}{\frac{8\pi r \cdot sin\phi cos\phi}{c(r) \cdot B \cdot C_t} - 1}$$

6. Calculate a and a′ using:

where B is the number of blades, c(r) is the local chord and r is the radial position of the control volume.

7. If a or a′ has changed more than a certain tolerance, go back to step 2 or else finish.

8. Compute the local loads on the segment of the blades.

In order to get good results, two corrections are applied to this algorithm: the Prandtl's tip loss factor, that corrects the assumption of an infinite number of blades, and the Glauert correction, which is an empirical relation between the thrust coefficient CT and the axial induction factor a for a > 0.2

$$F = \frac{2}{\pi} cos^{-1}(e^{-f})$$

$$f = \frac{B}{2}\frac{(R-r)}{r \cdot sin\phi}$$

approximately. The Prandtl's correction factor F is given by [1]:

$$C_T = \begin{cases} 4a(1-a) \cdot F, a \leq a_c \\ 4(a_c^2 + (1-2a_c)a) \cdot F, a > a_c \end{cases}$$

The Glauert correction for the thrust coefficient is given by [1]:

where ac is approximately 0.2.

By applying these two corrections to the algorithm, the equation for **a**, in step 6, is replaced by two equations [1]:

$$a = \begin{cases} \frac{1}{\frac{8\pi r \cdot F \cdot sin^2\phi}{c(r) \cdot B \cdot C_n} + 1}, a \leq a_c \\ \frac{1}{2}\left[2 + K(1-2a_c) - \sqrt{(K(1-2a_c)+2)^2 + 4(Ka_c^2 - 1)}\right], a > a_c \end{cases}$$

$$K = \frac{8\pi r \cdot F \cdot sin^2\phi}{c(r) \cdot B \cdot C_n}$$

For computig the loads in step 8, one is supposed to integrate the torque over the whole disc area, remembering that a and a′ are functions of r and φ, but as long as φ is also a function of r, they can be written as a(r) and a′(r) [9]:

$$P = \omega^2 \cdot \int_{r_0}^{R} 4a'(r)(1-a(r))\rho F V_0 \cdot \pi r^3 dr$$

In order to obtain total thrust T and total torque M, we can integrate from the following differential equations [9]:

$$dT = 4\pi r \rho V_0^2 a(1-a)F dr$$

$$dM = \omega \cdot 4a'(1-a)\rho F V_0 \pi r^3 dr$$

Therefore, we notice that: $dP = \omega dM.$

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Some parameters and constants used in the computations are given as follows:

- Water's kinematic viscosity: v = 1.002 · 10−6P a · s.
- Water density: ρ = 997 kg/m3.
- Number of blades: B = 3.

In order to set the hydrokinetic turbine's rotor blades' initial radius, we will use equation (36) with a power target of 900 W , an estimated efficiency of 90 %, a CP value of 0.4 (reasonably below the Betz limit of 0.593), and a speed V0 of 1.0 m/s. Thus, the radius is set to be: $R = \sqrt{\frac{2P}{\eta \cdot \pi \rho \cdot C_P \cdot V_0^3}}$ >>> $R = \sqrt{\frac{2 \cdot 900}{0.9 \cdot \pi \cdot 997 \cdot 0.4 \cdot (1.0)^3}} = 1.26\ m;$

which implies that the diameter and height of our designed turbine is supposed to be 2.52 m. But the

actual blade lengths will be reduced by a factor of 15 % due to the presence of the hub. So, the blade

lengths will range from a distance of 0.19 m from the axis to 1.26 m.

Therefore: R = 1.26 m, r0 = 0.19 m.

In our code, each of the blades is cut into 41 different sections, with a spacing of 0.02675 m between adjacent sections. So: N = 41.

The chord profiles used for the simulations were of two types: elliptic and linear. The corresponding equations are given by: $c_{elliptic} = 0.5\sqrt{1.05 - \frac{r}{R}},\ c_{linear} = 0.5 - 0.1(\frac{r}{R}).$

The local pitch angle θ was designed to have a linear variation along the blades, according to the

equation in degrees: $\theta_{linear} = 1^\circ - 5^\circ(\frac{n-1}{N-2}) = 1^\circ - 5^\circ(\frac{n-1}{41-2})$, for n ranging from 1 to 41.

The Glauert correction factor was set to: ac = 0.2.

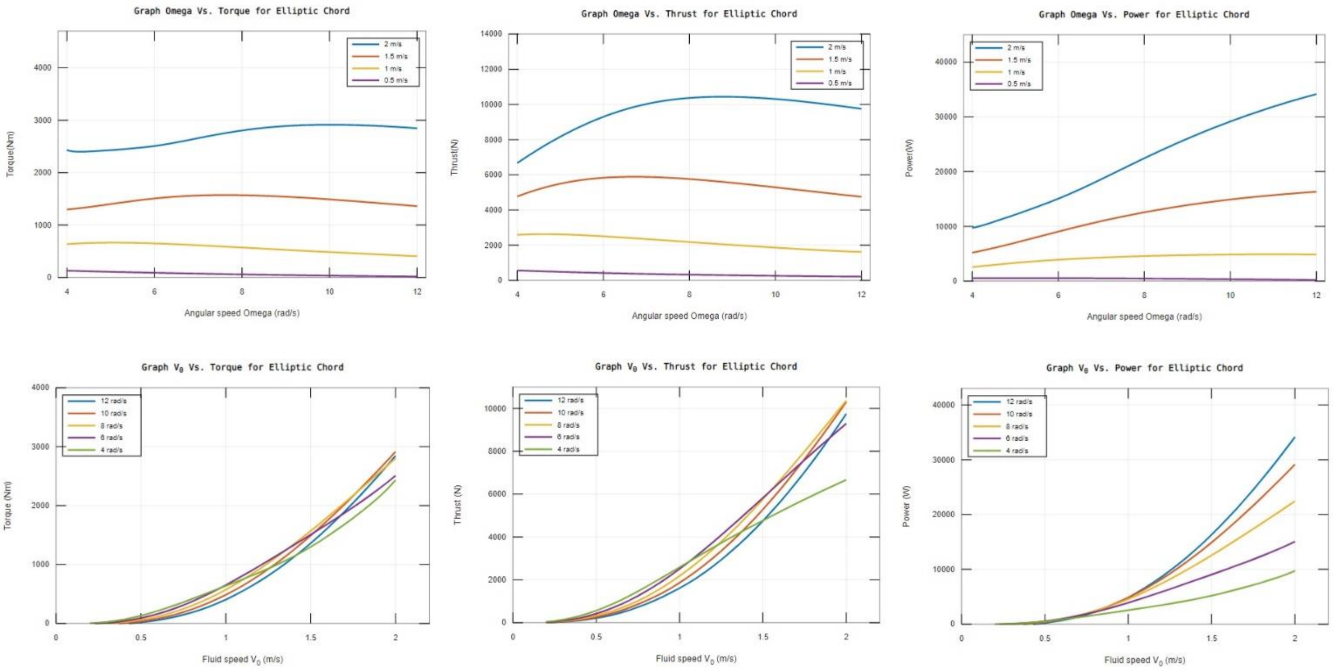
The average flow speed at Amazonas river ranges along the year from 0.735m/s to 2.27m/s, for dry and wet seasons respectively. But as the current turbine design is aimed for smaller rivers, we therefore use average speeds of Amazonas' river tributaries, except from Trombetas, Madeira and Xingu rivers, which present a maximum of 0.5m/s during dry season and a maximum of 2m/s during wet season [5]. But the speed water flow of Negro river, for instance, near the city of Manaus and before reaching its important tributary Tarumã-Açu river, can reach as low as 0.129m/s in February [4].

For the areas of Solimões river, close to the city of Manaus, the period of the year when the river remains at a high level comprises 60 to 160 days, and the low level lasts for 30 to 120 days, depending on the year. Additionally, the amount of time it takes for the river to oscillate from low level to high level ranges from 90 to 160 days, and from low level to high level it can range from 30 to 120 days [6]. In order to simplify calculations, we decided to calculate and plot of four different river speeds: V0 = 0.5, 1, 1.5, 2 m/s.

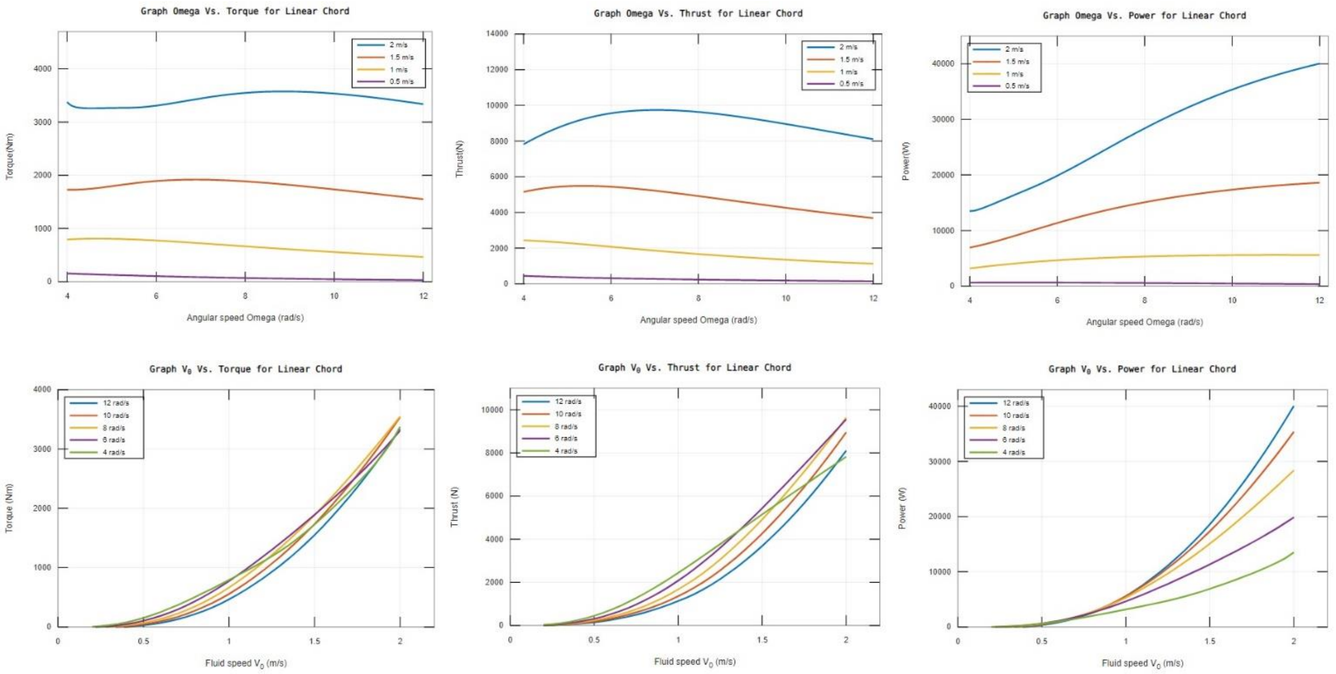
Due to difficulties related to implementing the interface between MATLAB and Xfoil, which would be used specifically for getting the Lift and Drag coefficients required by step 4 of the algorithm shown in section 1.3, we used tables of CL and CD coefficients according to given Reynolds number Re and angle of attack alpha, from the airfoiltools.com (for the Goettingen profile: *http://airfoiltools.com/airfoil/details?airfoil=goe410-il*). The tables provided by this website are obtained from Xfoil for Re = 50.000, 100.000, 200.000, 500.000, 1.000.000 and a range of negative and positive alpha values discretized by a difference of 0.25. In case we needed intermediate values, we interpolated linearly the coefficients CL and CD doubly, in terms of Re and alpha.

RESULTS:

The algorithm implemented in MATLAB yields graphs for Torque, Thrust and Power as functions of water speed (V0) or rotor's angular speed (Omega), for two different types of chords: Elliptic and Linear. The graphs for the Goettingen 410 profile are shown below. Firstly, the graphs for Elliptic Chord distribution, for Omega and V0 on the x-axis, respectively:



Secondly, the graphs for Linear Chord distribution, for Omega and V0 on the x-axis, respectively, showing the increased Power output:



CONCLUSIONS:

Results show that there is not a significant difference between the curves in general, and the Power output in particular, from the airfoils GOE410 and GOE420. Instead, there is a greater output for the case of the Linear chord, in comparison with the Elliptic one, for both of them. Thus, we conclude that any of the two profiles could be chosen but the Linear chord blade type is preferred instead of the Elliptic one.

Considering that the high tide periods are generally longer than the low tide ones, our theoretical river is more likely to spend most of the year above the 1 m/s flow speed. Setting the average annual flow 40 speed to the value of 1 m/s, we can estimate that average Power output would be of at least 2 kW , for the case of omega = 4 rad/s, as can be seen in Figure 17. Therefore, we can state that our initial Power goal, set to 900 W , will be surpassed easily during the year. From this perspective, the turbine configuration proposed could, at least theoretically, and assuming all the other assumptions and parameters exhibited in this text, be implemented and meet output expectations.

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