Horizontal Axis Wind Turbine Blade Design for the Urban Areas in Puerto Rico

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Abstract *— Horizontal Axis Wind Turbines are the preferred and most common method for power extraction from wind. In this study, the researcher will test three different airfoils to design a blade that optimizes wind energy generation, given the specific challenges that the Puerto Rican urban landscapes present. The researcher will use Blade Element Momentum Theory to analyze the performance of each of the airfoils given the specific variables present and choose a design that maximizes the power output of the wind turbine. The researcher will focus on the aerodynamic aspect of the design, focusing on the optimal geometry for generation. The SD7062 was found to be the optimal airfoil to be the optimal profile with an estimated power of approximately 700 W at the designated parameters.*

Key Terms *— Airfoil, Blade Element Momentum Theory, Power Coefficient, and Tip Speed Ratio.*

INTRODUCTION

According to [1], "Wind power is one of the fastest growing sources of new electricity supply and the largest source of new renewable power generation added in the United States since 2000." Wind power is clean, sustainable, and dependable making it a good candidate for countries looking to phase out fossil fuels as a mean of power generation. It is not only great in the large scale for countries but can also be implemented successfully at the small scale, bringing power generation to those who need it.

Puerto Rico currently has a Wind Power Capacity of 102 MW. This generation is mostly divided into two wind farms in Naguabo and Santa Isabel [2]. This is approximately 2% of the total generation for the whole island of Puerto Rico. This shows that Puerto Rico still has a long road towards the 100% renewable energy generation 2050 goal it has set.

One way to increase wind power generation in Puerto Rico is to use more of the available landscape, including urban areas. Although large scale wind farms are not feasible in many parts of Puerto Rico, smaller turbines and arrangements of turbines could be utilized.

There is one major challenge when implementing wind power in Puerto Rico, and that is the local wind speeds. The literature shows that Puerto Rico has an inland estimated wind velocity of 0 to 5.9 m/s, which lands it in the "Poor" Wind Power Density classification. There are select places along the coast and further inland where the velocities are higher, but wind speeds do not surpass the 5.9 m/s readings normally [3].

Looking for designs that better accommodate to the needs of Puerto Rico's environment and carefully selecting areas to implement the wind turbines, the island's journey to 100% renewable energy generation can be helped.

For the selection of the areas to implement the wind turbines, a case study was made for a residential area near the shore. The energy extracted, considering obstructions at an urban scale, are well within the average yearly energy consumed residentially in Puerto Rico [4]. The researcher can build upon this study using the wind lens technology to find better and more efficient solutions to the current obstacles for wind power generation.

Furthermore, the researcher can work with the airfoil design of the wind turbine to better suit Puerto Rico's wind conditions. According to [5], the analysis of aerodynamic conditions revealed that there are airfoil families better suited to work under a wind field speed of 2.5 m/s, which is well within Puerto Rico's estimated wind speeds.

Using all these ideas, the researcher can optimize efficiency and maximize energy generation using a wind turbine in an urban area or any other landscape in Puerto Rico.

WIND POWER GENERATION

The theory behind the generation of power from wind comes from Momentum Theory. Energy is extracted from the wind as it is transferred from the molecules in the air to the blades of the turbine. The total kinetic energy of a flowing fluid is described as [6]:

$$E_k = {}^1\!/_2\, m v^2 \quad (1)$$

Thus, Power is defined as:

$$P = \dot{E_k} = {}^1\!/_2\, \dot{m} v^2 \quad (2)$$

$$\dot{m} = \rho A v \quad (3)$$

$$P = {}^1\!/_2\, \rho A v^3 \quad (4)$$

In Figure 1 the researcher can see a representation of wind flowing through a turbine and the different section of velocity and pressure. The fluid loses velocity before and after close to the turbine, where the energy transfer happens. Also, a difference in pressure is created.

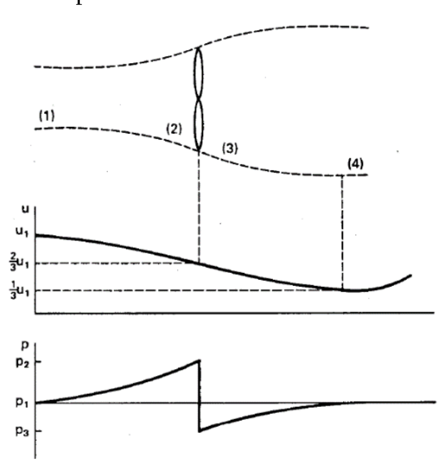

Figure 1

Wind tube flowing through turbine [7]

The transfer of energy happens when the force of the wind hitting the blades moves them. The thrust generated is then equal and opposite to this force and is defined as:

$$T = A(p_2 - p_3) \quad (5)$$

From conservation of linear momentum, we can write:

$$T = \dot{m}(v_1 - v_4) \quad (6)$$

Now because no work is done between stations 1 & 2, and 3 & 4 we can use Bernoulli's relations:

$$p_1 + {}^1\!/_2\, \rho v_1^2 = p_2 + {}^1\!/_2\, \rho v_2^2 \quad (7)$$

$$p_3 + {}^1\!/_2\, \rho v_3^2 = p_4 + {}^1\!/_2\, \rho v_4^2 \quad (8)$$

$$p_2 - p_3 = {}^1\!/_2\, \rho (v_1^2 - v_4^2) \quad (9)$$

Since the mass flow (3) at the turbine is now: $\dot{m} = \rho A v_2$

We apply the thrust equations (5) & (6):

$${}^1\!/_2\, \rho (v_1^2 - v_4^2) = \rho A v_2 (v_1 - v_4) \quad (10)$$

$$v_2 = {}^1\!/_2\, (v_1 - v_4) \quad (11)$$

And now we can define power in terms of the wind velocity:

$$P_{out} = T * v_2 = {}^1\!/_2\, \rho A v_2 (v_1^2 - v_4^2) \quad (12)$$

The Power Coefficient can then be defined as the efficiency with which wind energy into power. It is, in simple terms, the ratio of converted power to available power in the fluid flow. This aerodynamic coefficient is important because it will help find the optimal blade design for this study.

$$C_p = \frac{Turbine\ Power}{Wind\ Power} = \frac{P_{out}}{{}^1/_2 \rho A v_1^3} \qquad (13)$$

In an ideal world, C_p should be equal to 1, which would indicate that all the available power from the wind was extracted. But the Betz Limit tells states that C_p cannot go higher than 0.5926. In this study, the researcher wants to get as close as he can to that $C_{p,max}$ as possible.

BLADE DESIGN METHODOLOGY

To design a small wind turbine (50 kW or less rated power), optimizing the blade geometry is fundamental; this way the researcher maximize power generation and energy extraction from the wind.

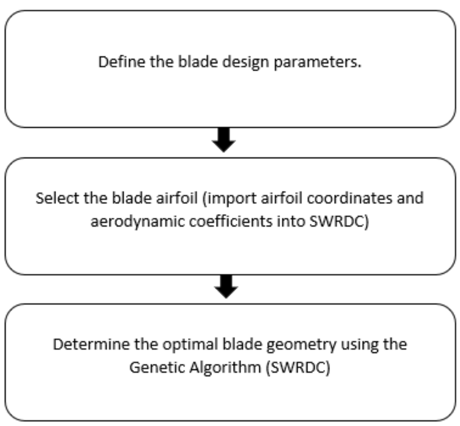

Figure 2

Flowchart for design and Analysis of Blades

The parameters for the wind turbine in this study are:

- Design Wind Speed = 5 m/s
- Number of blades = 3
- Design tip speed ratio = 7
- Design angle of attack = 0 deg
- Rotor radios = 2.5 m

The design speed for this turbine was chosen from empirical data taken with an anemometer in Bayamon, Puerto Rico. The data was taken in a period of days and the mean of the values was calculated to be approximately 5 m/s.

The design tip speed ratio was chosen to optimize efficiency and power output. The tip speed ratio for a 3 bladed turbine reaches optimum power around 5 to 7 range, which narrowed the selection [8]. A design tip speed ratio of 7 was chosen to generate as much power as possible.

The researcher will be analyzing 3 different airfoils for this scenario. These airfoils were chosen because of their performance at low wind speeds. The Reynolds numbers in this study range from Re = 100000 to Re = 2000000 for all airfoils to be able to better understand the aerodynamic properties of the airfoils.

The chosen airfoils were:

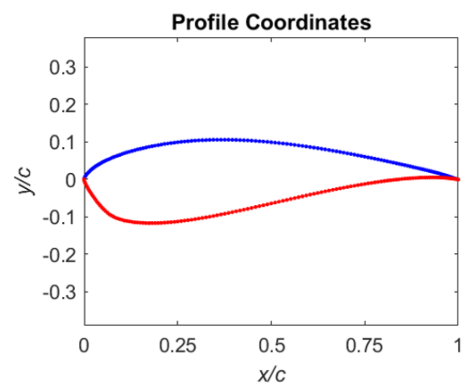

Figure 3

SD7062 Profile

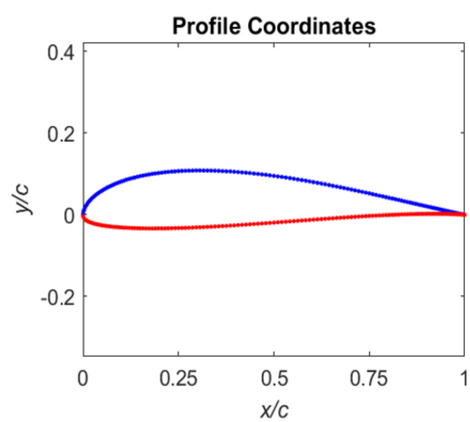

Figure 4

S823 Profile

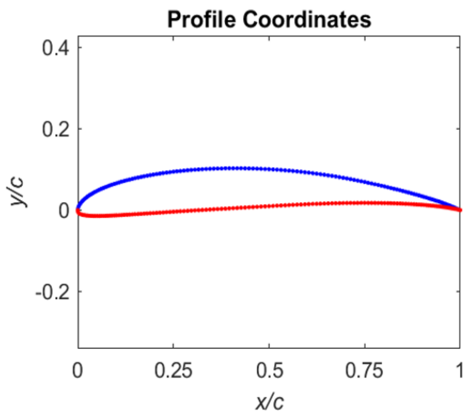

Figure 5

SG6043 Profile

The polar coordinates for the airfoils were obtained using XFOIL, which is an interactive program for the design and analysis of subsonic isolated airfoils [9]. These polar coordinates contain the Lift and Drag coefficients of the airfoils at various angles of attack, in this case from -180 deg to 180 deg.

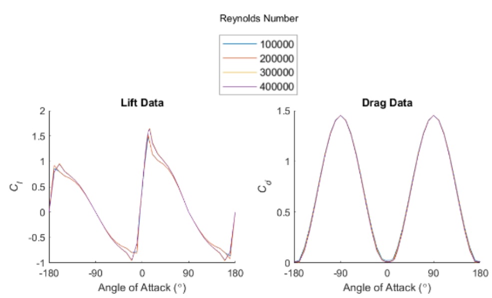

Figure 6

SD7062 Polar Coordinates

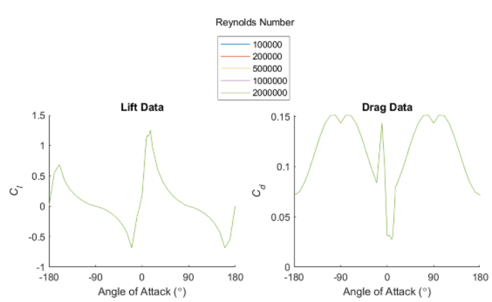

Figure 7

S823 Polar Coordinates

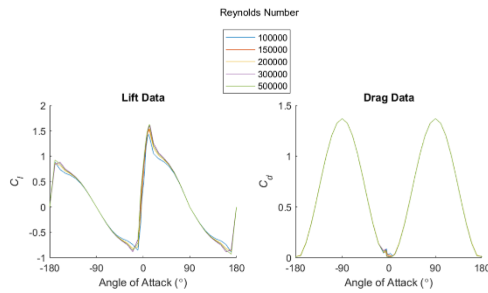

Figure 8

SG6043 Polar Coordinates

After obtaining the polar coordinates the researcher then used the SWRDC code to determine the chord and twist angle distributions for the airfoils [10]. The blades were divided into 30 sections in which the localized chord and twist would be optimized. These distributions are optimized to obtain the highest Cp possible, and this is done with a Genetic Algorithm. The algorithm works by optimizing the criterions (i.e., chord and twist angle) by minimizing or maximizing its objective function. A weighted min-max problem is used for the design of the blades as follows:

$$Minimize\ max_{i=1}^{q} W_i \times \left[\frac{f_i(x)-z_i^{min}}{z_i^{max}-z_i^{min}}\right] \qquad (14)$$

Where q is the number of objectives, W_i are weights that satisfy $W_i \geq 0$ and $\sum_{i=1}^{q} W_i = 1$, $f_i(x)$ are the objective functions, and Z_i^{max} & Z_i^{min} are the values of the population in the present iteration. The values of x most be within the region that satisfy the constraints [10].

SWRDC uses the following vector for its calculations:

$$\begin{bmatrix} W_1 \frac{C_p(i)-C_p^{min}}{C_p^{max}-C_p^{min}}, \\ W_2 \frac{T_{st}(i)-T_{st}^{min}}{T_{st}^{max}-T_{st}^{min}}, \\ (1-W_1-W_2)\frac{m_B(i)-m_B^{min}}{m_B^{max}-m_B^{min}} \end{bmatrix} \qquad (15)$$

The parameters utilized for the different blade design runs were:

- Population size = 120
- Number of generations = 150
- Mutation index = 20
- Crossover type – Simulated binary crossover (SBX)
- Mutation probability = 0.0555
- Crossover probability = 0.9

RESULTS

In this section, the different chord and twist distributions and the performance results for the given parameters will be found. These distributions have been optimized for power generation, and thus for these conditions they are close to the maximum power the airfoils can produce.

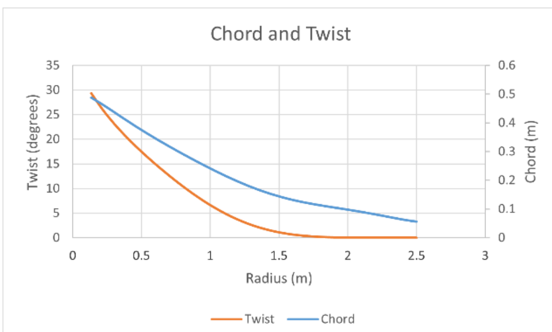

Figure 9

S823 Chord and Twist Distribution

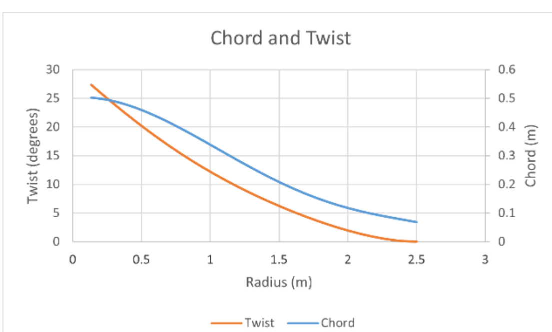

Figure 10

SD7062 Chord and Twist Distribution

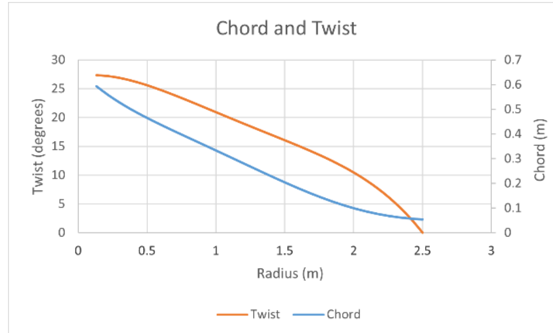

Figure 11

SG4063 Chord and Twist Distribution

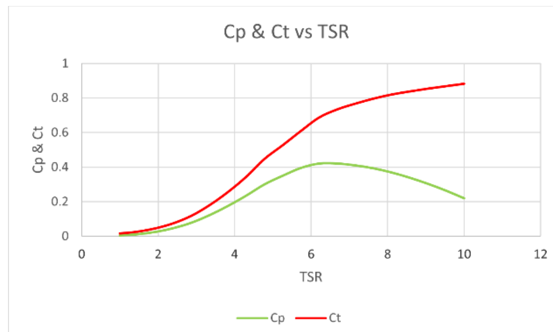

Figure 12

S823 Cp and Ct

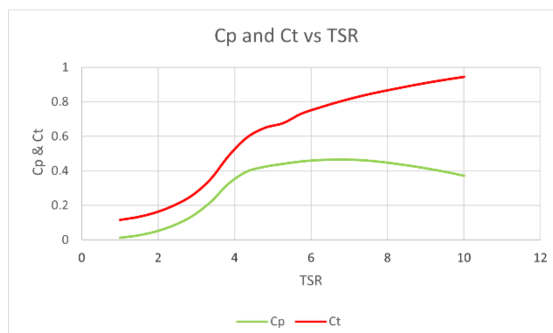

Figure 13

SD7062 Cp and Ct

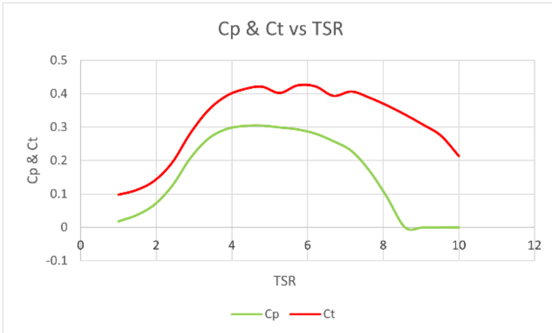

Figure 14

SG6043 Cp and Ct

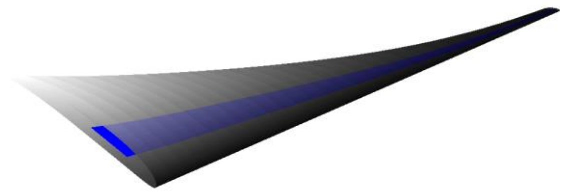

Figure 17

SG6043 3D Render

Table 1
Performance Results (SWRDC)

Airfoil	Power Coefficient	Power (W)	Torque (N-m)	Thrust (N)
S823	0.414588551	623.2515	44.51796	227.8984
SD7062	0.464156841	697.7675	49.84054	245.4222
SG6043	0.239376681	359.8552	25.70395	116.7018

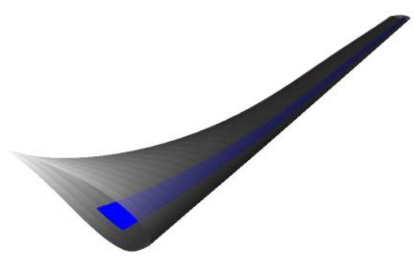

Figure 15

S823 3D Render

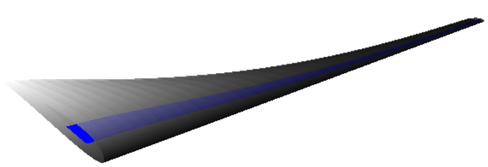

Figure 16

SD7062 3D Render

DISCUSSION

After running SWRDC for all three airfoils, using the previously presented parameters, the researcher obtained the different optimized chord and twist distributions.

After conducting an aerodynamic analysis for a small horizontal wind turbine using each airfoil, the performance solutions marked a distinct difference between each airfoil. This difference will help the researcher choose the optimal airfoil for the conditions of the study.

Looking at the performance results, a relation between the different parameters can be noticed. It is shown that as the Power Coefficient increases the Power, Torque, and Thrust also increase. This makes sense because as discussed previously, the Power Coefficient is the ratio between generated power and total power available in the fluid flow. As more power is extracted from the same conditions of flow, more Torque and Thrust are experienced.

The researcher can also confirm that the most power generation occurs at $6 < TSR < 7$. This means that any faster than that would only be detrimental to power generation and durability of the turbine.

The S823 airfoil had the largest twist angle of the three at 29.35 degrees. It was also the one with the narrowest chord of 0.4872 at the beginning of the airfoil. The airfoil performed very well with a Cp of 0.4146, giving it a power of 623.25 W. But as the TSR increased past the optimal value, it is shown that it had a substantial decrease in power, even though torque and thrust kept increasing.

The SD7062 is the all-around best performing airfoil of the three. It had a maximum twist angle of 27.35 degrees and a maximum chord of 0.5021 m. With a Cp of 0.4641 and a power of 697.77 W it outperformed both other airfoils. Although after the optimal TSR the Cp starts decreasing, it is not as steep as the other two airfoils.

The SG6043 is by far the lowest performer of the three airfoils, with a Cp of 0.2394 and a power of 359.85 W. For this airfoil optimal TSR was around 4 or 5 and after that power, torque and thrust rapidly decrease. After a TSR of 8 the airfoil stopped producing power. This maybe because the blades were going so fast that they were running into turbulent air from the previous blade, thus reducing the generated power.

CONCLUSION

An aerodynamic analysis and design procedure were done for three different airfoils. Using tools such as XFOIL and SWRDC, the analysis of the aerodynamic coefficients, chord, and twist for the different blades was done and these parameters were optimized for power generation.

The best performing airfoil in this study was the SD7062 with and estimated power of 697.77 W at 5 m/s wind velocity, 2.5 m blade radius, 7 TSR and a 0-degree angle of attack.

The purpose of this study was to design a horizontal wind turbine to fit the needs of the urban area in Puerto Rico. This design is a preliminary attempt to reach this goal. With a 2.5 blade radius and a 700 W approximate power generation capability, it is compact enough and scalable enough to fit specific situations in the urban landscape of Puerto Rico.

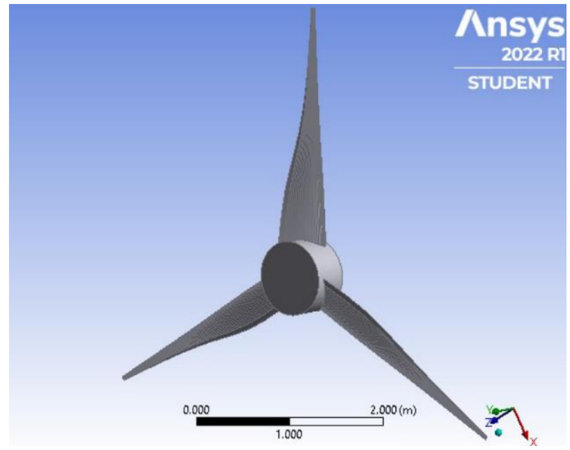

Figure 18

3D Render of SD7062 Turbine

FUTURE WORK

These results were the product of an iterative mathematical solution through different algorithms. A good way to verify this data would be to carry out a CFD simulation of the SD7062 airfoil with the discussed initial parameters. This would add validity and would bring it closer to actual numbers.

One very important limitation to this study was the wind velocity parameter. Puerto Rio does not generally have high speed winds inland. A way to solve this problem could be the implementation of a wind lens to the current turbine design. This technology has been shown to increase efficiency in low-speed horizontal wind turbines and would be an interesting analysis to perform.

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