Experimental Comparison of Energy Generation between Conventional and Wavy Leading Edge Blades in HAWT

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***Abstract*—Horizontal Axis Wind Turbine (HAWT) is one of the most important devices for electricity generation from Wind Energy, and design of new blades has become a fundamental research field to improve the efficiency and to reduce cost of this system. This article presents a preliminary comparison between two micro Wind Turbines (WT), one with standard blades and another one with Wavy Leading Edge (WLE) morphology, inspired by the flippers of the humpback whale, to work at low-speed wind conditions. To perform a correct validation, the authors propose a four steps approach for the design, manufacture and test of a WT. First, the design of the blade, followed by the design of the Wind Turbine (WT). Next step is the manufacture of two functional models, one with WLE and another with standard blades, to make a relative comparison, and, finally, the acquisition of real-time data from these systems for the corresponding analysis in terms of energy generation. Results show that the WLE has an increase of over 20% in energy production in all the tests that were performed, with respect to the standard blade.**

***Index Terms*—Energy generation, experimental comparison, HAWT, wavy leading edge, wind turbine**

I. INTRODUCTION

Each year, a new record is achieved in the amount of greenhouse gases trapped in the atmosphere [1]. The sources of electricity generation in countries such as the United States are the second largest source of greenhouse gas emissions after the transport sector [2]. In this way, the electric generation from wind energy has had an exponential growth during the last years [3], being the Horizontal Axis Wind Turbine (HAWT) the most common Wind Turbine (WT) type due to its balance in cost-efficiency and an important social and aesthetic factor [4], [5].

In general, the index of cost-efficiency is measured taking into account the investment in the system with respect to the produced energy ($/kWh). To reduce this index, different strategies have been implemented such as the generation of new shapes of blades and designs based on biomimetics with the aim of generating more efficient systems inspired by natural forms and behaviors, other strategies come from the analysis of the manufacturing methods and process of the WTs blades [6], to the analysis of the meteorological conditions that the installation place must have, since good wind conditions are crucial for the proper functioning of the system, even considering that the wind behaves stochastically [7]. In this way, new shapes for more efficient blades should be explored and analyzed.

II. RELATED WORK

This analysis is oriented to different designs of WT blades, found in literature and commercial options, where biomimetic inspiration is proposed. Herrera *et al*. [8] and Chu and Chong [9] proposed a WT bio-inspired by the movement of the falling seeds of trees, reporting that this type of WT turbine has better performance than commercial ones for low speed areas. Cognet *et al*. [10] reported a WT with folding blades that passively deform under aerodynamic loads and centrifugal effects. This work was inspired by how insects fly and how plants reconfigure itself. Fish *et al*. [11] reported riblet-surface, based on the texture of sharks skin, as a way to decrease the drag, which in terms of a WT would be a possible increase of torque. Finally, Zhang and Wu [12] reported an increase in output power for speeds between 10-20 m/s for blades bio-inspired in the fins of humpback whales, called Wavy Leading Edge (WLE). Miklosovic *et al*. [13] performed an experimental validation, with a wind tunnel, between a surface with WLE and a smooth surface, where they conclude that this type of geometry, for systems that need lift especially at low wind speeds, is a very important alternative. Zhang *et al*. [14] reported an increase of 25 - 39.2% in the lift coefficient at certain angles of attack and a decrease of 20% in the drag coefficient for these leading edge protuberances. These researches justify the effort for new designs with WLE and validation of feasibility for efficiency improvement.

III. APPROACH

WLE is based on the operation of the bumps of the fins of the whales to decrease the drag coefficient (C_d), which

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allows to increase the lift coefficient (C_l) by 20 %, improving aerodynamic efficiency and taking better advantage of wind conditions [15]. In order to validate, in an experimental way, the performance of this type of geometry with respect to a conventional one, the purpose of this article is to make a comparison, in terms of electric generation, between two HAWTs, of Diameter, D =1.1 m (see Fig. 1), so that they can work simultaneously under the same conditions. An urban context is presented as a case study. It is important to clarify that these two WTs will be controlled with respect to the Yawing, according to the monitoring of the wind currents. For this purpose, conventional blades are aerodynamic shapes that have a continuous surface following the trajectory of an airfoil, without any type of undulation or abrupt change in shape.

This experimental validation is implemented with a four steps approach. First, the design of the blade, followed by the design of the WT. Next step is the construction of the two prototypes, and, finally, the acquisition of real-time data for the corresponding analysis in terms of energy generation. Next, the different steps of the approach are explained altogether with the implementation and results.

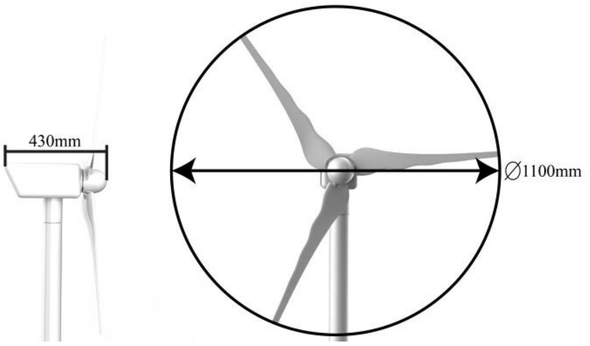


Fig. 1. Design proposal for WT.

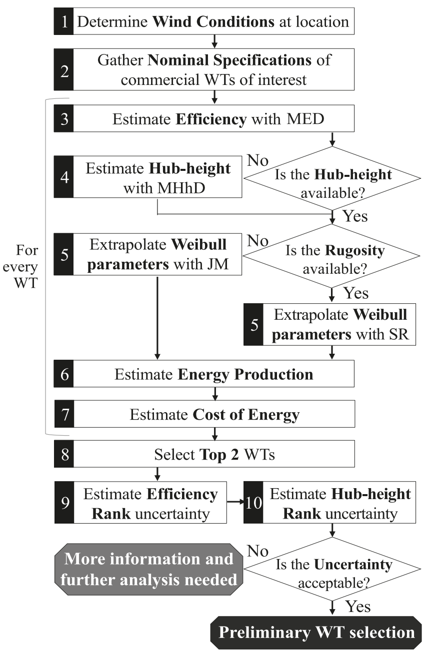


Fig. 2. WT selection method [16]

TABLE I: ECLECTIC STEALTHGEN D400 (WARWICK TESTED)

Characteristic	Value
Diameter	1.1m
Sweep Area	0.95m2
Cut in Speed	2.5m/s
Tip Speed Ratio (TSR)	7

A. Blade Design

Since location conditions are crucial to the design of WTs, as wind speed determines the characteristics of the blades, authors propose the design of the two blades (WLE and conventional) for the meteorological conditions of the city of Medellín, Colombia, using the software Albatros Create®, which generates the 3D model of the WTs, used to manufacture them. Therefore, a design was made based on WT selection method proposed by Arias-Rosales and Osorio-Gómez [16], and presented in Fig. 2. This method was used up to step 6, since it allows to validate whether the design of a WT is cost-efficient. This is relevant for designing the blades according to the conditions of a particular location.

Next, each step of the process is explained.

1) Determine wind conditions at location

First, the air density (ρ) should be found with Equation 1. It depends on air pressure (p) and temperature (T), where (h_{asl}) is the altitude above sea level, which are calculated as follows:

$$\rho = \frac{p}{287.04T} \tag{1}$$

$$p = 101325\left[1 - \frac{0.0065h_{\mathrm{asl}}}{288.15}\right]^{5.2561} \tag{2}$$

$$T = 288.15 - 0.0065h_{\mathrm{asl}} \tag{3}$$

After solving the equations for the specific conditions of the city of Medellín, the air density for Medellín was found to be ρ = 1.06 kg/m^3, after which the average wind speed was determined by means of a data set taken from the “Sistema de Alerta Temprana” (SIATA). The average wind speed (v_p) was determined to be 1.7 m/s at 3 m altitude.

2) Gather nominal specifications of commercial WT

In this step, depending on the specifications, similar commercial WTs are considered, since there is certain information that can be obtained from them. The following specifications are obtained from the Eclectic StealthGen D400 WT, see Table I, and, from the data set presented by Arias-Rosales and Osorio-Gómez [16].

3) Estimate efficiency

The efficiency of the WT is also taken from the specifications in the data set presented by Arias-Rosales and Osorio-Gómez [16]. For this kind of WTs the efficiency (η) is 0.3033.

4) Estimate hub-height

Hub-Height is determined as the height at which the turbine design data is taken, for this case, we used the data taken from the meteorological station of SIATA at 3m of height, this is used as input to generate a Weibull distribution and find the scale (c_1) and shape (k_1) parameters, where c_1 is calculated by

$$c_1 = v_p \Big/ \Gamma\left(1+\frac{1}{k_1}\right) \quad (4)$$

Here k_1 is found from a Weibull calculator where the wind speed dataset of the last year in the city of Medellin is entered, obtaining a k_1 value of 1.53, which is below the ideal (k_1 =2), and c_1=1.88 from the equation. With these parameters the Weibull distribution presented in the Fig. 3 is obtained.

5) Extrapolate weibull parameters

Although the minimum height of a WT concerning the lower surface must be a minimum of 10 m, due to issues related to regulations, proximity to the airport and others, installations of this height are not allowed. So, the calculation to 6 m of height was executed. Taking into account and knowing that the Hub-Height is at 3 m height, an extrapolation of the scale (c_2) and shape (k_2) factors was carried out, obtaining a parameter c_2 = 2.29, and k_2 = 1.61, as it is presented in Fig. 3.

6) Estimate energy production

After obtaining the scale and shape factors and characterizing their behavior, the energy is obtained with a Riemann sum, and the speed that maximizes the energy is found. This summation is given as

$$E = \frac{1}{2}\rho A\eta t \sum_{i=1}^{r} v_i^3 f\left(v_i\right) v \quad (5)$$

where A is the swept area, t is the hours in one year, and v_i is located in the middle of the v_Δ, that is the width of Riemann rectangles.

This results in the energy for each speed interval, taking as starting point v_Δ= 2.5 m/s, with a 0.5 m/s increase in speed, as it is presented in Table II.

From the table it can be concluded that the speed that maximizes the energy for wind behavior in the city of Medell ́n is v_d = 2.5 m⁄s, it means the design speed.

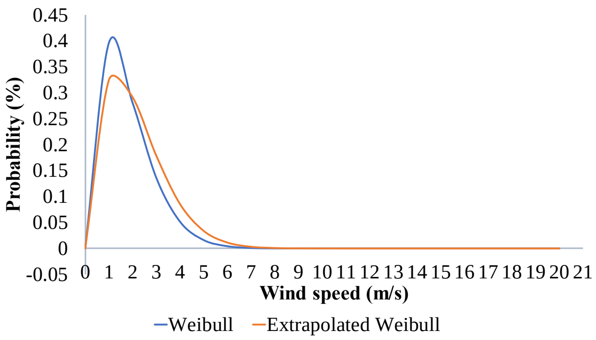


Fig. 3. Weibull distribution according to local wind conditions

TABLE II: SPEED WHICH MAXIMIZES THE GENERATION

i	Wind speed(m/s)	Energy(W/h)
1	2.5	487388.627
2	3.0	117669.884
3	3.5	682.6
4	4.0	0.0405
5	4.5	8.9007E-09

TABLE III: CHARACTERISTICS OF BLADE SECTIONS

Blade Section	Reynolds	L_{ct}(m)	Radius(m)	Mach	α(°)
Root	8857	0.036	0.01	0.010	7.6
1	56737	0.081	0.1	0.029	10.2
2	54903	0.064	0.15	0.036	10.2
3	50929	0.051	0.2	0.041	10.4
4	47123	0.043	0.25	0.046	10.8
5	43840	0.036	0.3	0.051	10.9
6	41057	0.031	0.35	0.055	11
7	38698	0.027	0.4	0.058	4.9
8	36674	0.025	0.45	0.062	4.9
9	34907	0.022	0.5	0.065	4.9
10	33377	0.02	0.55	0.068	4.5

TABLE IV: FINAL PARAMETERS FOR BLADE DESIGN.

Section	L_{ct} (m)	WLEL$_{ct}$ (m)	Ω(°)
A1	0.081	0.096	15.44
A2	0.064	0.064	8.23
A3	0.051	0.059	2.8
A4	0.043	0.043	0.63
A5	0.036	0.040	-0.22
A6	0.031	0.031	-0.56
A7	0.027	0.029	-0.59
A8	0.025	0.025	-1.4
A9	0.022	0.022	-3.05
A10	0.020	0.020	-3.08

TABLE V: WAVY LEADING EDGE DESIGN

WLE Type	Amplitude of first bump	WLE Length
Parabolic Wavy	0.01261m	0.55m

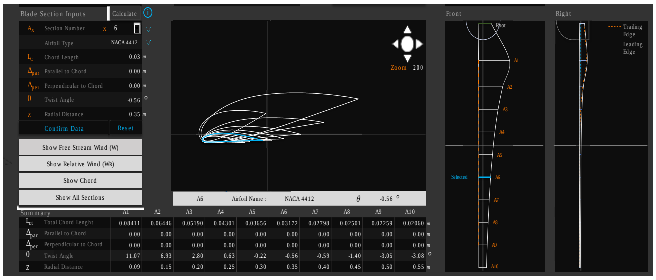
7) Determine the angle of attack

This step is carried out additionally to the methodology, since after obtaining the design speed (v_d) the next step is to find the Reynolds number for each profile considered in the blade. Here it is important to mention that the design of the WTs was carried out with the software Albatros Create®, which divides the blade in 10 sections. To find the angle of attack (Ω) for each section, the first step is to determine the string or length of each section (L_{ct}) using the optimization method of Schmitz, which is already considered in this software, and then, to define the Lift Constant (C_l = 1). In addition, the alpha angle (α) is determined for each section with the software Q-Blade®, for the highest value with respect to the lift over drag ratio (C_l/C_d), that is an input for the Schmitz optimization to determine the angle of attack (Ω) for each section. Table III and Table IV present the results for each section of the blade.

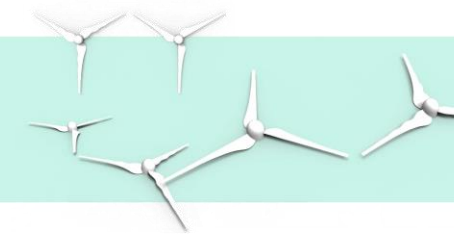
8) 3D model design

The angle of attack for each section of the blade was considered in the software Albatros Create® (see Fig. 4 (a)) resulting in the final 3D model of both WTs, as it is presented in the Fig. 4 (b). To generate the blade with WLE, the amplitude of the first bump is added to the value of the chord of section A1 (WLEL$_{ct}$), and then, the type of the curve is defined. In this case, a parabolic shape is selected, which models the shape up to the specified distance (WLE lenght). For the aerodynamic shape of the blade a NACA-4420 profile was used in the first section, and for the rest of the sections a NACA-4412 was selected.

The parameters presented in the Table V were used for the design of the WLE blade in the software Albatros Create®.

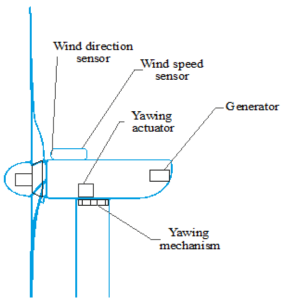


(a) Design in Albatros Create



(b) CAD model

Fig. 4. 3D model final design.



(a) Diagram of components

(b) Render fianal concept

Fig. 5. Wind turbine design.

B. Wind Turbine Design

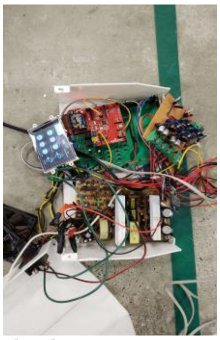
For performance validation, a systematic process of design and construction of two WTs must be carried out; for which the mechanical, electro-mechanical and control operation of the system must be defined. This would allow to identify, through similar generation systems, the influence of the change of the blade profile on the generation efficiency.

As a final result of the WT design process a proposal is obtained, as it is presented in Fig. 5. Such design has different mechanical and monitoring systems that allow the operation and testing phase, obtaining data and acting in real time.

C. Prototyping

ABS in 3D printing is used for the development of the blades avoiding significant differences in their physical properties, such as weight, surface roughness or moment of inertia, mainly because it is sought that the only differentiating factor in the generation of energy between the blades, will be the geometry with or without WLE and not any of the variables mentioned above. Metal parts were manufactured for the chassis and transmission systems. ServoMotors were used for the movement of yawing, Brushless Motors were used for the electric generation, and Arduino MEGA, with a Wattmeter, were used for control and measurement. The final prototypes and their main components could be observed in Fig. 6.

(a) Mechanical components



(b) Electronic components

(c) Wind Turbines

Fig. 6. Final prototype.

TABLE VI: START-UP AND "CONSTANT ROTATION" TESTS

	Conv	WLE	Conv	WLE	Conv	WLE	Conv	WLE
Ω_1	15 °	15 °	27 °	27 °	33 °	33 °	39 °	39 °
Start alone	NO	NO	NO	NO	NO	YES	NO	YES
Const rotation	NO	NO	YES	YES	YES	YES	YES	YES

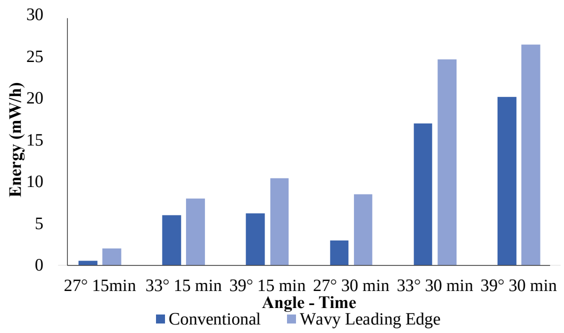


Fig. 7. Energy measurements for both turbines at different angles of attack.

D. Experiment and Results

The WTs were tested in a test-bed that generates wind speeds in a range of 2 m/s to 3 m/s. Different angles of attack (Ω_1) in the first section of the blade were set up in order to validate which of the two turbines starts more easily, and if they generate after starting, as it is presented in Table VI. Following this, the electric generation of each WT is validated in tests consisting in leaving the turbines for 15min and 30min, in different angles of attack, and measuring the amount of energy generated. These results are presented in Fig. 7.

The first observation is that for the angle of attack of the first section, Ω_1 = 15.44°, none of the WTs is capable to start nor to maintain rotation. This could be explained since the air flow that was used could be completely turbulent. However, changing the angle of attack, the WT with WLE has obtained a better performance considering that for angles greater than 27° it is able to keep rotating, and for angles of attack greater than 33° it starts by itself unlike the conventional blade that at no time is able to overcome the inertia and starts by itself.

Another important result is that, in terms of energy generation, WLE always generated more than conventional WT, where there was an improvement greater than 20% in all tests. It is important to clarify that every time when less than 40mW were generated, the resolution of the sensor was not able to measure below this value. However, this allows to define that the WTs with WLE have better performance for low wind speed and turbulent flows.

IV. Conclusions

In summary, two functional models of WTs were designed and manufactured for the wind conditions of the city of Medellín, Colombia. Besides, experimentally, the implementation of biomimetics for a micro WT obtained better results with respect to a conventional one, being more stable in terms of energy generation considering the changes in the angles of attack. This allows to think about the implementation of larger scale WTs where this technology could be, in terms of cost-benefit, a promising alternative to be implemented.

Further work is oriented to validate these two implementations in real wind conditions with higher wind speeds. Another objective is the implementation of new materials for the blades, since for high wind speeds the ABS is not very reliable because it does not have a resistance as high as fiberglass, composites, or some metal.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Santiago and Gilberto conducted the research; Santiago performed the experiments; Santiago and Gilberto analyzed the data; Santiago and Gilberto wrote the paper; Santiago and Gilberto had approved the final version.

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