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EXPERIMENTAL MEASUREMENTS ON BIOMIMETIC WIND TURBINE BLADES BY Q. MULTIFLORA SEED

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Abstract. Inspired by wind dispersing seeds, this paper presents the performance study of a small-prototype horizontal axis wind turbine (HAWT) by means of low-speed wind tunnel testing. The rotor blade design was based on the Q. Multiflora seed from the Brazilian's Cerrado vegetation. To evaluate and compare the power coefficient, c_p, a baseline conventional rotor blade was built entirely based on Blade Element Momentum (BEM) theory. Both small HAWT have been tested for low wind speeds commonly found in countryside of Brazil, such as 4 up to 6 m/s. An experimental workbench was designed and built to properly measure the rotational speed, output power and torque for the prototype tested. The choice of wind dispersing seed, such as Q. Multiflora has shown potential for future insights on designing's inspired by nature.

Keywords: biomimetic, wind turbine, Q. Multiflora, blade shape, aerodynamics

1. INTRODUCTION

The global wind potential has motivated projects for the design and optimization of wind turbines for the different application ranges. Brazil, in this scenario, presents a timid participation of the wind power in its energy matrix, however this situation is changing gradually.

Among possible ways of research, we have the interdisciplinarity between engineering and Biomimetics, a science inspired by nature to design innovative solutions, has contributed significantly in this context, especially in the mimesis of seeds and fruits dispersed by anemochories. Its basic principle is to have nature as a model, measure and mentor of the design process (Queiroz et al. 2016). In the field of wind energy this holistic science has fostered significant technological development.

In this context, this research, inspired by a seed that enable robust aerodynamic force production and stable flight, proposes a simplified initial (preliminary) biomimetic blade model (prototype) for horizontal axis wind turbine (HAWT) rotor blade with the objective of evaluating the mimesis potential of the schizocarp of seeds of anemochory species of the Brazilian *Cerrado* and achieving a high integral power coefficient, Cp, over a broad range of tip-speed ratios, and hence enhances robustness in aerodynamic performance. As mentioned, this is an ongoing research started at the end of 2018 and improving along the upcoming years, since it is necessary a broad spectrum of methodologies and interdisciplinarity to correctly evaluate this mimesis effect in the HAWT.
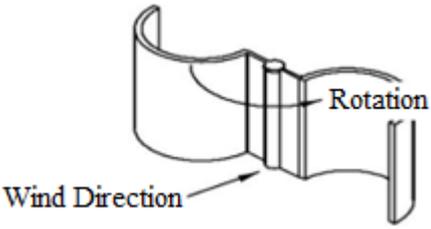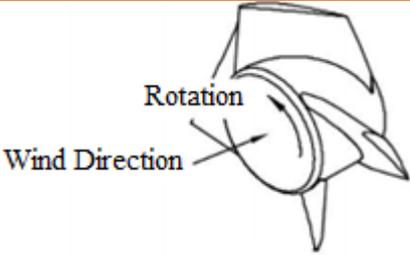
2. LITERATURE REVIEW

2.1. Horizontal axis wind turbine (HAWT)

Horizontal axis wind turbines are the most common type of wind turbine used commercially and domestically nowadays. As these turbines are parallel to the direction of the free flow, they are called the horizontal axis wind turbine. The HAWT propulsion principle works with the fundamental principle of lift, as shown in Fig. 1. In this way, the torque generated to rotate the turbine is produced as a result of the pressure difference on the upper and lower surfaces of the wind turbine blade. One of the advantages of using a horizontal axis wind turbine is listed below:

o Highly efficient in terms of energy extraction from the wind;
o Proven reliability as it has been used extensively in the commercial applications;
o Cost effective.

According to the theory of the linear moment, it assumes that there is no rotation of flow in the wake of the turbine. However, the flow leaving the turbine has a constant rotation and moves downstream. The torque applied to the turbine by the air moving through it requires equal and opposite torque imposed on the air, causing the air to rotate in the opposite direction of the turbine.

Propulsion	Drag	Lift
Diagram		
Maximum Theoretical Efficiency	16%*	50%**

* Gasch, 2002.
** Burton, 2011.

Figure 1. Comparison of the lift and drag mechanism.

The existence of a rotational flow in the conveyor results in less energy being extracted by the turbine and, as a result, losses in the kinetic energy occur. According to Eggleston & Stoddard (1987), the most vulnerable wind turbines with large losses of kinetic energy that cannot be recovered are those with low speed of rotation and high torque. There are minimal losses, however, for wind turbines that have higher speed of rotation and less torque.

2.2. The biomimetic wind turbine background

The Brazilian's Cerrado, the most biodiverse savanna on the planet, occupying about 23,9% of the national territory (ICMBio, 2007), has an ample collection of anemometric propagules, fruits and seeds that are dispersed by anemochory with the most diverse aerodynamic patterns, between species with winged, feathery and light adaptations capable of aligning against the airflow direction during its descent and subsequently self-rotate or rotate during its descent.

Since the greater flatness of the anemocoric seeds, in general, allows better stability in the air, it is possible to use biomimetics, the application of plant and animal design, which is being used to solve various problems of engineering, materials physics, medicine and other knowledge by providing innovative models for industrial products. The application of this idea arose from a work in partnership between the Experimental Aerodynamics Research Center (CPAERO) with the Institute of Biology (ICBIO) from Federal University of Uberlândia, where the purpose was to evaluate the dispersion of *Cerrado*'s seed by means of using a conventional wind tunnel (WT). By first understanding the flow characteristics of these seeds, it was possible to propose this work.

Thus, it has been proposed that these geometrical properties can be used in the design of blades of horizontal axis wind turbines (HAWT) biomimetically. This would consist of three flexible blades that allows the yaw and passive mechanism during its operation. As a preliminary study it is believed that improvements and ideas would lead to a consistent prototype to be continuously tested as this research progress.

3. METHODOLOGY

3.1. Tools and equipment

This work deals with a theoretical-experimental research, applied to the analysis of the air flow in the blades of two small wind turbines (HAWT) with three, aiming to obtain the coefficients of power, torque, rotation of the axis and other parameters that allow the characterization of the performance of a wind turbine. To do this, using two types of additive manufacturing, two small-scale models were constructed: an initial simplified prototype of a dynamic-size model of a seed for wind tunnel testing is provided and compared to a baseline model of blades, rotor and hub and simplified fairing.

Firstly, it was necessary to analyze the velocity distribution in the cross section of the tunnel with the help of a hot wire anemometer. With the velocity profile of both models, the static torque of the prototype is determined by the use of a developed equipment coupled to the axis of the equipment, which records all readings for a velocity range from 2 m/s to 10 m/s. A photo-tachometer was used to measure the rotation of the model in free rotation against the flow. With the data obtained, it was determined the static torque curve and the RPM curve as a function of the incident velocity. Through the experimental determination of the incident velocity profile and velocity profile in the aerodynamic runway

of each turbine, the flow rate of the flow was determined, and the power extracted by the rotors in free rotation is evaluated.

The following resources and equipment used from the Experimental Aerodynamics Research Center (CPAERO) of the Federal University of Uberlândia will be used for the research, according to Fig. 2.
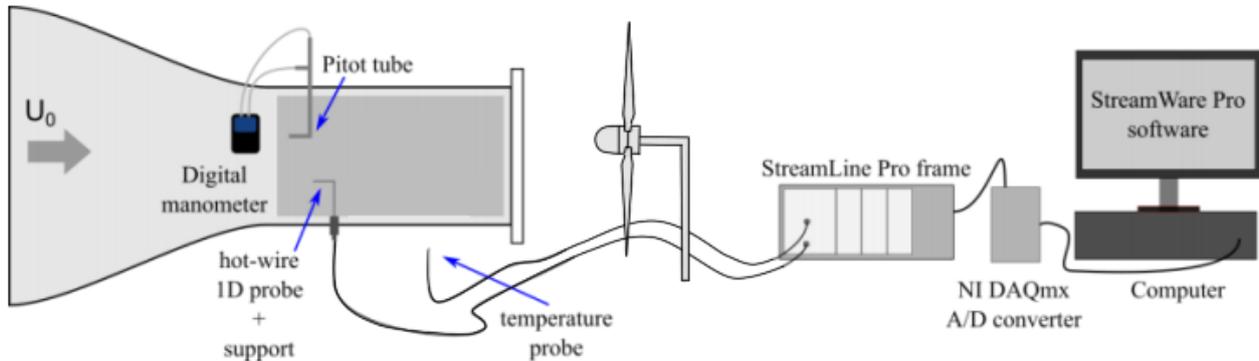

Figure 2: Laboratory apparatus used in this study.

The experiments were carried out in the 60×60 cm^2 Wind Tunnel, shown in Figure 3. Flow momentum was created by a rotor of 12 blades driven by a 25Hp electrical engine. The maximum air speed in the tunnel test section is approximately 30 m/s with minimal blockage.

The hot-wire anemometry was used to produce velocity profiles upstream and downstream the model. All streamwise velocity measurements were performed using the DANTEC Dynamics Streamline Pro Anemometer System with a 1D hot-wire probe (55P11) and a 90° support.

A Pitot tube was placed on the roof of the test section and a digital manometer displayed the free stream velocity. The velocity indication was used to define global free stream flow stagnation and start anemometer acquisition.

For the fixing of the blades a bench was developed to measure the performance of aerogenerators in scale, so that the blades were easily coupled and decoupled from the hub – Fig. 3.

Figure 3: Bench for measuring performance of wind turbines at scale

3.2. Biomimetic wind turbine geometry modelling

For this research, seeds with autogiro morphology were chosen, as shown in Fig. 4. These are characterized by being winged seeds on one side only, which provides the means for dynamic propulsion: it rotates firmly around the seed at the end of the diaspore (Augspurger, 1986).

The fruit collections of the four species were carried out in the reserve of the Hunting and Fishing Club *Itororó* de *Uberlândia* (CCPIU). Among the variety of seeds found, *Qualea Multiflora* was chosen, which is popularly known as wood-land, country-land-wood, broad-leaf wood, *ariavá*, among others (Corrêa, 1978). It is a native tree species of the Brazilian's *Cerrado*, which occurs in the riparian forests and in the broad *cerrado*, widely distributed from the Legal Amazon to São Paulo, Minas Gerais, Goiás and Mato Grosso, and is generally found in high, dry and well drained areas (Almeida et al., 1998; Lorenzi, 2000).
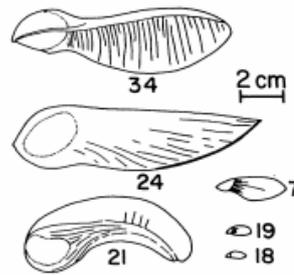
Figure 4: Examples of self-tapping seeds (Augspurger,1986).

Seeds of *Q. Multiflora* from the *Cerrado* biome were collected to generate the geometric profiles of the biomimetic lamina. An average of the contour points of a seed was used to generate a profile at different angles of vision using the *SolidWorks* and *Catia* software, giving the leading edge, curvature and trailing edge of the proposed blade.


(a) Q. Multiflora Tree

(b) Side view of the seed

Figure 5: Q. Multiflora tree and its seed original shape.

To evaluate and to compare the HAWT blade performance, a reference (baseline) of a blade model attached to a three-blade wind turbine with a rotor diameter of 0.45 m was used – Fig.6. The biomimetic design did not have any optimizations in the analysis during the accomplishment of this work, being the first analyzes in this type of configuration. A thickness of 5 mm was imposed for the blade. For application purposes, the root region of the blade has been strengthened so as not to break due to the properties of the sheet. Unfortunately, due to some procedural errors during the execution of the geometry the diameters of the rotors differ slightly, however the difference was properly considered in the calculations.
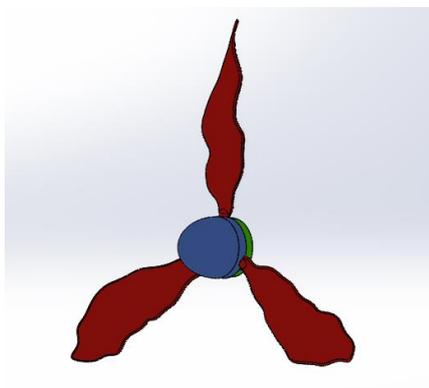
(a) Biomimetic design
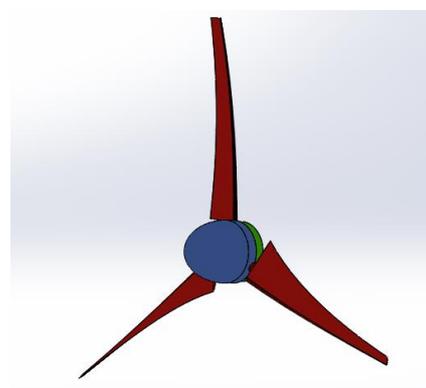
(b) conventional design (baseline)

Figure 6: Scaled model prototypes – CAD 3D drawing.

For the comparison of results, it was used as a baseline prototype – Fig.6(b) with the wind generator design settings as follows:

- o Number of blades: 3
- o blade tip speed ratio: 7
- o Efficiency for blades: 0.4
- o Spade radius: 1 m
- o Wind speed: 10 m / s
- o Torque generator: 10.95 N.m
- o Power Generation: 766.5 Watts
- o Generator speed: 70 rad / s

The final product for both conventional (baseline) and biomimetic design of the blade prototypes are illustrated in Fig.7. After the CAD drawing process, both blades were manufactured by a deposition process using a 3D MakerBot® Replicator Z18 printer, by means of PLA material of 1.75 mm of diameter. The whole process for printing 3 blades took about 24 hours and later, a surface finishing was carried out by means of polishing and painting the blades.

Figure 7: Final scaled model prototypes (conventional and Multiflora blades).

4. PRELIMINARY RESULTS

This section is devoted to present the preliminary results from this ongoing research. The results are divided in measurements from the vertical velocity profile upstream and downstream the rotor plane, rotation per minute (rpm) and a more simplistic way of torque measurement from both conventional and biomimetics' blades.

4.1   Speed Profile measurement

Using a hot wire anemometer, it was possible to quantify the velocity at 1 m in the Hub's posterior plane with the wind tunnel at 6 m/s and the blades fixed at the angle of 4 °. The measurements were taken starting from 5 cm from the axis's center (Point P1) and moving vertically the anemometer every 5 cm up to 50 cm (Point P10), covering the whole radius of the wind turbines. Thus, the relationship between velocity and blade geometry was perceptible – Table 1.

Table 1. Experimental results for velocity.

Baseline	4°	Q.Multiflora	4°
P_1	5,3	P_1	4,5
P_2	5,4	P_2	4,5
P_3	5,4	P_3	4,8
P_4	5,3	P_4	5,0
P_5	4,7	P_5	5,0
P_6	4,8	P_6	4,4
P_7	3,9	P_7	4,3
P_8	3,5	P_8	2,6
P_9	3,0	P_9	2,8
P_{10}	2,1	P_{10}	2,2

4.2 RPM measurement

A digital photo tachometer (Fig. 8) was used to determine the (rpm) of the HAWT prototypes with a precision of 0.05%. This type of device triggers a laser that reflects on the rotating surface and records the measurement through photo-electronic means. In the specific case, the apparatus was positioned after the turbine and the hub and it was fixed in the workbench and at least three measurements were taken for averaging the final value of rpm. The results for the conventional and biomimetic prototypes are summarized in Table 2.

Figure 8: Photo tachometer digital equipment.

Table 2. Experimental results of RPM.

	Baseline	Q. Multiflora
V[m/s]	**RPM**	**RPM**
4	86,30	126,8
5	122,00	187,57
6	158,97	259,96
7	202,23	319,73
8	240,77	374,97
9	270,83	427,20
10	311,87	493,73

Figure 9 illustrates the rpm curves for both baseline and Multiflora HAWT designs. The results showed that the autogiro capability of the seed (*Q. Multiflora*) is observed and quantitatively expressed in the results, since for the whole set of flow speeds the rpm was higher than the conventional configuration. A very important point to mention here is that the incidence angle of the Multiflora blade was not properly investigated. The Multiflora blade was fixed in a position relatively close to 4° in the hub. However, it is not sure that this is the best assembly configuration for obtaining the best aerodynamic response from the seed. This is one of the future works that will be assessed in the continuation of this research.
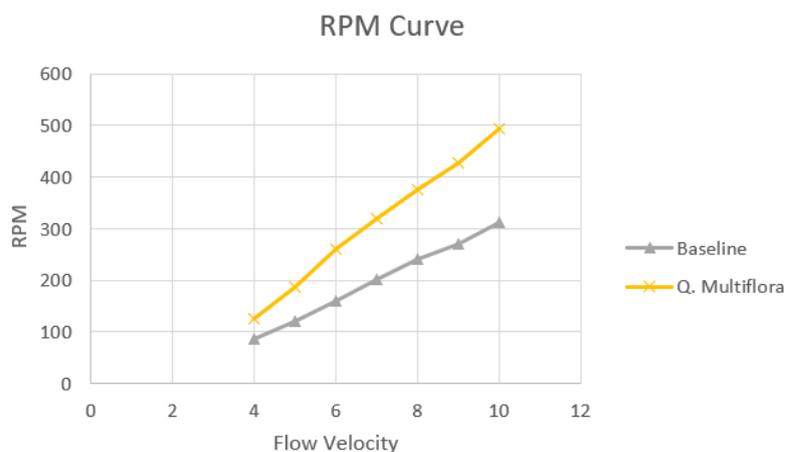

Figure 9: RPM for prototypes at different wind speeds.

4.3 Torque measurement

According to Borges (2015), the torque measurement of a rotating shaft may present some difficulties, due to the rotary movement and the need for power and the input / output of the system connected to the shaft. Due to the lack of resources for acquiring a digital torque measurement system at the time of this study, a simplistic physical procedure was considered and it is described as follows:

In order to measure the torque of the axis of rotation, a simple method was used, consisting of a system using an "arm" and a digital tensile scale, as shown in Fig. 10. For force measurement, the "arm" was placed horizontally and this one was connected with the axis of the turbine, so that when under the flow, the axis rotates, moving the arm which implies a force in the balance.

In this system, the mass applied to the end of the "arm" was recorded and the resulting weight could be evaluated. From the analysis of the applied forces, with the aid of a free-body diagram, Fig. 10, it can be deduced that the force actually applied on the axis is given by:

$$F_{axis} = m_{balance} \cdot g \tag{1}$$

in which F_{axis} is the resulting force applied to the axis [N], $m_{balance}$ is the mass measured in the digital traction balance [g], and g is the acceleration of gravity [9.81 m/s^2].

For the determination of the torque in the shaft, it is possible to multiply the force resulting in the axis by the lever arm, whose value is determined by:

$$T_{axis} = F_{axis} \cdot D \tag{2}$$

Where T_{axis} is the torque in the [Nm] axis and D is the length of the lever arm relative to the center of the axis [m].
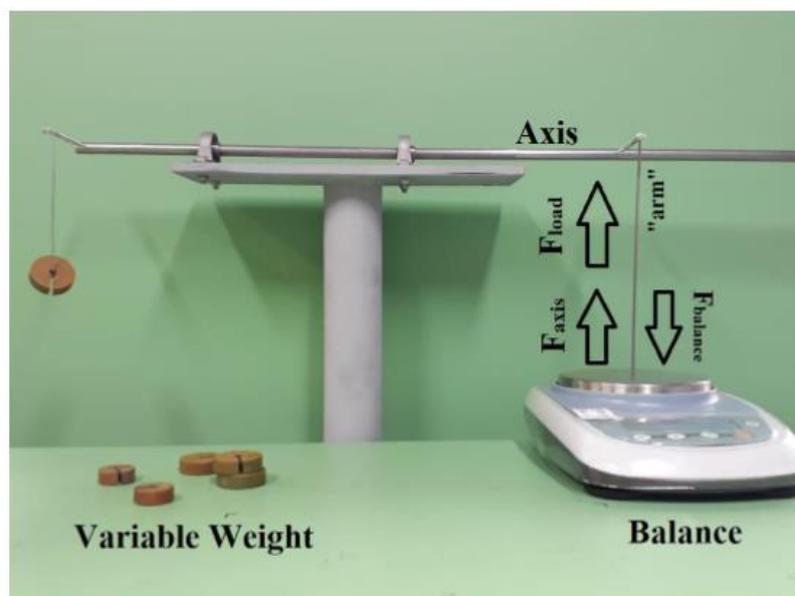

Figure 10: Mechanism developed to measure shaft torque.

This torque system was previosly calibrated with standard mass to provide the right weight in one side of the axis (input) while the force and torque were evaluated at the other extremity (output). The maximum error encontered in this approach was consistently less than 10% for all measurements. Also, due to lack of time to present these results, the torque system was not calibrated against an industrial digital torque measurement, which arrived at the final stage of this study. The static torque evaluation was performed with a frequency variation of the fan electric motor from 4 to 10 m/s, with increments of 1 m/s. The tests with the prototypes were done in a comparative system of data collection. Table 3 shows how the baseline and biomimetic prototype behave in the wind tunnel. For a reduction in measurement uncertainty, three measurements were performed for each flow velocity condition. Figure 11 shows the static torque curve, with a range of 4 to 10 m/s.

Table 3. Experimental results of Torque.

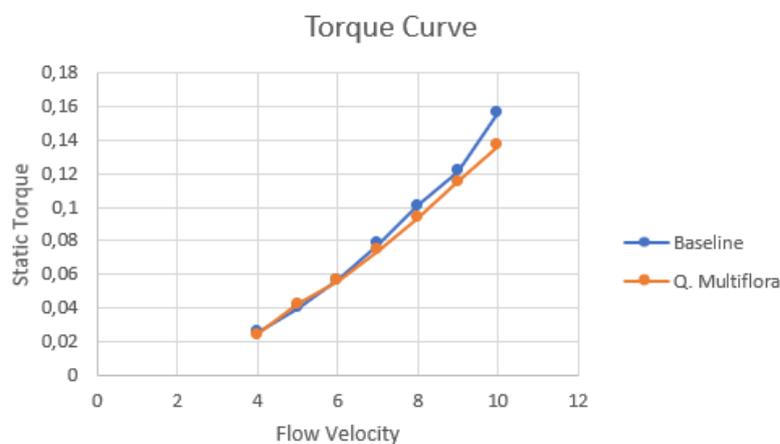|	Baseline		Q. Multiflora	
Temperature [°C]	27		24	
Autostart [m/s]	2,3		2,8	
V[m/s]	Weight [N]	Torque [N.m]	Weight [N]	Torque [N.m]
4	0,269	0,025	0,251	0,024
5	0,422	0,040	0,444	0,042
6	0,598	0,057	0,590	0,056
7	0,822	0,078	0,782	0,074
8	1,063	0,101	0,987	0,094
9	1,277	0,121	1,214	0,115
10	1,649	0,157	1,441	0,137

Figure 11: Static torque for the HAWT prototypes for different wind speeds.

The results obtained points towards a good relationship between angular velocity and torque for the *Multiflora*-based design. Once the rpm is higher for the biomimetic design and the torque is kept almost the same, it is hoped that there is margin for improvement in the current design, as for instance the optimization of the blade position. Also, it is expected that the auto starting could be improved with a new set of bearing and couplings in the workbench. This will be a task for future work.

5. CONCLUSION

This work presented a preliminary approach for measuring the performance of a biomimetic horizontal-axis wind turbine inspired by anemocoric seeds from the Brazilian's *Cerrado*. Two prototypes were designed and built to provide means of comparing and evaluating the results. Both small HAWT have been tested for low wind speeds commonly found in countryside of Brazil, such as 4 up to 10 m/s. An experimental workbench was designed and built to properly measure the rotational speed, output power and torque for the prototypes tested. The choice of wind dispersing seed, such as Q. Multiflora has shown potential for future insights on designing's inspired by nature.

Due to the novelty of this approach, future steps for a deeply understanding of the aerodynamics of the anemocoric seed are envisaged. At the moment, it is possible to identify and list the following activities:

- Aerodynamic analysis of the force coefficients (lift and drag) of the Q. Multiflora seed by means or wind tunnel measurements;
- Numerical analysis of the blade profile characteristics by using computational fluid dynamics (CFD);
- More sophisticated approach for measuring the maximum torque generated by the HAWT;
- Optimization of the aerodynamic shape of the blade;
- Improvement of the workbench for diminishing the friction in bearings and other system losses;

By considering the continuation of this research it will be possible to corroborate the potential gains in the efficiency of a bioinspired design, and eventually opening new possibilities for a growing Market of small HAWTs.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE