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Vertical Axis Wind Turbine Designed To Utilize Turbulence Created by Frequently Passing Trains

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Abstract— the thesis focuses on the complete design of a small vertical axis wind turbine for utilization of turbulence created by frequently passing trains. The aerodynamic analysis is performed implementing a momentum based model on a mathematical computer program. A three bladed wind turbine is proposed as candidate for further prototype testing after evaluating the effect of several parameters in turbine efficiency, torque and acceleration. The results obtained indicate that aluminium is a suitable material for rotor construction and a further development of the computer algorithm is developed in order to improve the flow conditions simulation.

Index Terms— Train Air Turbulence, Small Wind Turbine, Vertical Axis, VB Program



1 INTRODUCTION

As addressed by the title, the machine should be a wind turbine generating power using wind generated by fast and frequent motion of trains. No engine can produce work without dumping certain amount of energy to the ambient environment. The train moves on the track i.e. it changes its own space coordinates, certainly falls under the category of thermodynamic work. This should imply that, train dumps some energy to its surrounding environment, abiding to the Second Law of Thermodynamics. We here, are getting focused on the turbulence in air created by the train. It certainly can never happen naturally unless the train changes its space coordinates at some rate.

The aim of the project is to make an affordable turbine, made locally with available materials in developing countries, so that, it may be employed, on large scale, so as to utilize turbulence created by metro trains, which have considerable frequency to meet demand of around 1kW power.

Renewable and sustainable energy is one of the most important challenges currently facing mankind. Wind has made an increasing contribution to the world's energy supply mix, but still remains a long way from reaching its full potential. In this paper, we investigate the use of artificial evolution to design vertical-axis wind turbine prototypes that are physically instantiated and evaluated under approximated wind tunnel conditions. An artificial neural network is used as a surrogate model to assist learning and found to reduce the number of fabrications required to reach a higher aerodynamic efficiency, resulting in an important cost reduction.

In recent years, wind has made an increasing contribution to the world's energy supply mix. However, there is still much to be done in all areas of the technology for it to reach its full potential. Currently, horizontal-axis

wind turbines (HAWTs) are the most commonly used form. However, "modern wind farms comprised of HAWTs require significant land resources to separate each wind turbine from the adjacent turbine wakes. This aerodynamic constraint limits the amount of power that can be extracted from a given wind farm footprint. The resulting inefficiency of HAWT farms is currently compensated by using taller wind turbines to access greater wind resources at high altitudes, but this solution comes at the expense of higher engineering costs and greater visual, acoustic, radar and environmental impact". This has forced wind energy systems away from high energy demand population centers and towards remote locations with higher distribution costs. In contrast, vertical-axis wind turbines (VAWTs) do not need to be oriented to wind direction and can be positioned closely together, potentially resulting in much higher efficiency. VAWT can also be easier to manufacture, may scale more easily, are typically inherently lightweight with little or no noise pollution, and are more able to tolerate extreme weather conditions.

However, their design space is complex and relatively unexplored. Generally, two classes of design are currently under investigation and exploitation: the Savonius, which has blades attached directly upon the central axis structure; and the Darrieus, where the blades—either straight or curved—are positioned predominantly away from the central structure. Hybrids also exist. The majority of blade design optimization is performed through the use of computational fluid dynamics (CFD) simulations, typically described with three-dimensional Navier-Stokes equations.

2 TURBINE TYPE

Vertical Axis Wind Turbines (VAWT): the rotational axis is perpendicular to the wind direction or the mounting surface. The main advantage is that the generator is on ground level so they are more accessible and they don't need a yaw system. Because of its proximity to ground, wind speeds available are lower.

The design idea is to make a lift type turbine, with straight blades instead of curved. This kind of device is also called giromill and its power coefficient can be higher than the maximum possible efficiency of a drag type turbine, like Savonius.

3 AERODYNAMIC ANALYSIS

In this section, the rotor design parameters are described as well as the model used to calculate its aerodynamic performance. The model limitations are exposed and the computer algorithm and its validation are presented.

3.1 Wind Turbine Design Parameters

The wind turbine parameters considered in the design process are:

- Swept area
- Power and power coefficient
- Tip speed ratio
- Blade chord
- Number of blades
- Solidity
- Initial angle of attack

3.1.1 Swept area

The swept area is the section of air that encloses the turbine in its movement, the shape of the swept area depends on the rotor configuration, this way the swept area of an HAWT is circular shaped while for a straight-bladed vertical axis wind turbine the swept area has a rectangular shape and is calculated using:

$$S = 2 R L \quad (1)$$

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Where, S is the swept area [m²], R is the rotor radius [m], and L is the blade length [m]. The swept area limits the volume of air passing by the turbine. The rotor converts the energy contained in the wind in rotational

movement so as bigger the area, bigger power output in the same wind conditions.

3.1.2 Power and power coefficient

The power available from wind for a vertical axis wind turbine can be found from the following formula:

$$P_w = 0.5 \rho S V_o^3 \quad (2)$$

Where, V_o is the velocity of the wind [m/s] and ρ is the air density [kg/m³], the reference density used its standard sea level value (1.225 kg/m³ at 15°C), for other values the source (Aerospaceweb.org, 2005) can be consulted. Note that available power is dependent on the cube of the airspeed.

The power the turbine takes from wind is calculated using the power coefficient:

$$C_p = \frac{\text{Captured mechanical power by blades}}{\text{Power in wind}} \quad (3)$$

C_p value represents the part of the total available power that is actually taken from wind, which can be understood as its efficiency.

There is a theoretical limit in the efficiency of a wind turbine determined by the deceleration the wind suffers when going across the turbine. For HAWT, the limit is 19/27 (59.3%) and is called Lanchester-Betz limit (Tong, 2010, p. 22).

For VAWT, the limit is 16/25 (64%) (Paraschivoiu I., 2002, p. 148). These limits come from the actuator disk momentum theory which assumes steady, in viscous and without swirl flow. Making an analysis of data from market small VAWT the value of maximum power coefficient has been found to be usually ranging between 0.15 and 0.22.

This power coefficient only considers the mechanical energy converted directly from wind energy; it does not consider the mechanical-into-electrical energy conversion, which involves other parameters like the generator efficiency.

3.1.3 Tip Speed Ratio

The power coefficient is strongly dependent on tip speed ratio, defined as the ratio between the tangential speed at blade tip and the actual wind speed.

$$TSR = \frac{\text{Tangential speed at the blade tip}}{\text{Actual wind speed}} = \frac{R \omega}{V_o} \quad (3)$$

Where ω is the angular speed [rad/s], R the rotor radius [m] and V_0 the ambient wind speed [m/s]. Each rotor design has an optimal tip speed ratio at which the maximum power extraction is achieved.

3.1.4 Blade Chord

The chord is the length between leading edge and trailing edge of the blade profile. The blade thickness and shape is determined by the airfoil used, in this case it will be a NACA airfoil, where the blade curvature and maximum thickness are defined as percentage of the chord.

3.1.5 Number of Blades

The number of blades has a direct effect in the smoothness of rotor operation as they can compensate cycled aerodynamic loads. For easiness of building, four and three blades have been contemplated.

3.1.6 Solidity

The solidity σ is defined as the ratio between the total blade area and the projected turbine area (Tullis, Fiedler, McLaren, & Ziada). It is an important nondimensional parameter which affects self-starting capabilities and for straight bladed VAWTs is calculated with (Claessens, 2006):

$$\sigma = \frac{N c}{R} \tag{4}$$

Where, N is the number of blades, c is the blade chord, L is the blade length and S is the swept area, it is considered that each blade sweeps the area twice.

This formula is not applicable for HAWT as they have different shape of swept area.

Solidity determines when the assumptions of the momentum models are applicable, and only when using high $\sigma \geq 0.4$ a self starting turbine is achieved (Tong, 2010).

3.1.7 Initial Angle of Attack

The initial angle of attack is the angle the blade has regarding its trajectory, considering negative the angle that locates the blade's leading edge inside the circumference described by the blade path.

3.2 Blade performance initial estimations

It is interesting to have a low value of design wind speed as it will ensure more availability of electrical energy supply with averaged and frequent airspeeds.

The turbines found on the market are rated by their maximum power output; this could give false expectative

on the final user as the rated wind conditions can be higher than the average wind conditions. Table 1 shows what were the initial estimated performance of the wind turbine, the power coefficient and tip speed ratios had been estimated analyzing the data taken from similar market wind turbines and making an average.

TABLE 1
 PERFORMANCE PARAMETERS AND ROTATIONAL SPEED INITIAL ESTIMATIONS FOR THE DESIGN WIND SPEED

Power Performance initial estimation			
Design Parameters		Calculated Parameters	
Rotor radius (m)	1	Swept area (m ²)	4
Blade Length (m)	2	Solidity	0,8
Blade Chord (m)	0,2		
Power Coefficient	0,17	Rated blade speed (m/s)	12
Tip speed ratio	2	Actual Rotational speed (rad/s)	12
Number of blades	4	Actual Rotational speed (rpm)	114,59
Air constants			
Air density (Kg/m ³)	1,225		
Wind speed (m/s)	6	Power Available from wind (W)	529,2
Conversion factors		Power output (W)	
rad/s --> rpm	9,54		89,964

3.3 Aerodynamic Model

In order to model the performance of a vertical-axis wind turbine there are four main approaches (Cooper, 2010):

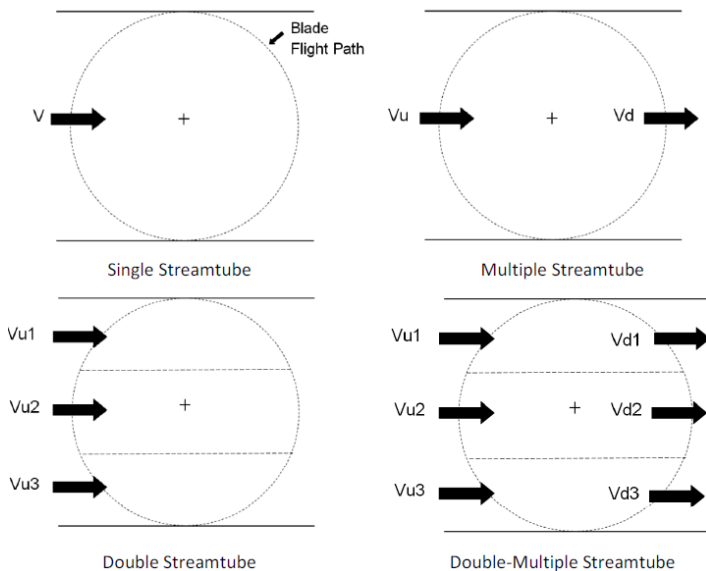
- Momentum models
- Vortex models
- Local circulation models
- Viscous models
- Computational Fluid Dynamics (CFD)

Each model has its advantages and drawbacks, the main advantage of momentum models is that their computer time needed is said to be much less than for any other approach (Spera, 2009).

Computational fluid dynamics was considered in first place but the time needed for mesh generation in three dimensional analyses was supposed to be too large for the purposes of the present thesis.

The model chosen for the aerodynamic analysis is the double-multiple streamtube with variable interference factor, often abbreviated DMSV, which is enclosed in the momentum models category and is based in the conservation of momentum principle, which can be derived from the Newton's second law of motion. It has been used successfully to predict overall torque and thrust loads on Darrieus rotors.

FIGURE 1
 STREAMTUBE MODELS USED FOR VERTICAL AXIS WIND
 TURBINES ANALYSIS ADAPTED FROM SPERA, 2009



This analytical model was developed by I. Paraschivoiu for determining aerodynamic blade loads and rotor performance on the Darrieus-type wind turbine with straight and curved blades (Paraschivoiu I., 2002).

The model uses the actuator disk theory, two times, one for the upstream and one for downstream part of the rotor. This theory represents the turbine as a disc which creates a discontinuity of pressure in the stream tube of air flowing through it. The pressure discontinuity causes a deceleration of the wind speed, which results in an induced velocity.

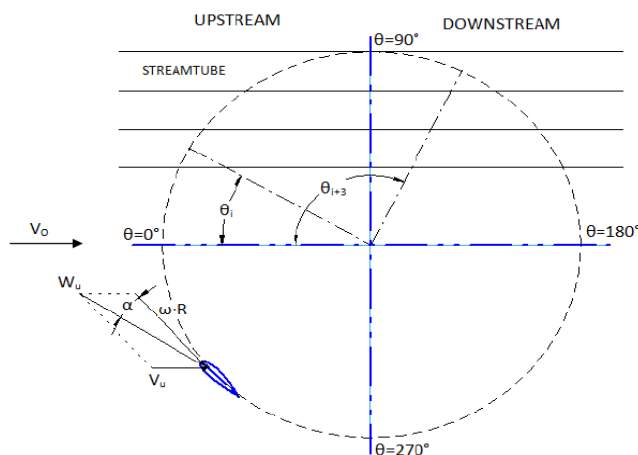
The swept volume of the rotor is divided into adjacent, aerodynamically independent, streamtubes; each one is identified by his middle θ angle, which is defined as the angle between the direction of the free stream velocity and the position of the streamtube in the rotor (see Figure 2).

The analysis of the flow conditions is made on each streamtube using a combination of the momentum and blade element theories, the former uses the conservation of the angular and linear momentum principle and the later divides the blade in N elements and analyzes the forces on the blades (lift and drag) as a function of blade shape. Further details on blade element momentum theory can be found on Manwell, McGowan and Rogers, 2009, p. 117-121.

It is assumed that the wind velocity experiments a deceleration near the rotor, if we represent the front and rear part of the turbine by two disks in series, the velocity

will be decelerated two times, one for the upstream and the other for the downstream. Unlike for the analysis of a troposkien shaped Darrieus turbine, it has been assumed no vertical variation of the induced velocity as a straight vertical blade is subjected to the same flow velocity along its length.

FIGURE 2
 DIVISION OF THE ROTOR SWEEP AREA INTO STREAM TUBES,
 DEFINITION OF VELOCITIES AND ANGLES



According to Paraschivoiu (2002) the induced velocity decrease in the axial streamtube direction in the following manner:

The induced velocity in the upstream part of the rotor is:

$$V_u = V_o au \tag{6}$$

Where, V_u is the upstream induced velocity, V_o is the free stream air velocity and au is the upstream interference factor, which is less than 1 as the induced velocity is less than the ambient velocity.

In the middle plane between the upstream and downstream there is an equilibrium-induced velocity V_e :

$$V_e = V_o (2 au - 1) \tag{7}$$

Finally, for the downstream part of the rotor, the correspond-ing induced velocity is:

$$V_d = V_e ad \tag{8}$$

Where, V_d is the downstream induced velocity and ad is the downstream interference factor which is smaller than the upstream interference factor.

Knowing the induced velocities all around the blade trajectory will allow us to calculate the lift and drag forces associated to every blade position and then, these forces can

be related to the torque and power coefficient produced by the wind turbine.

The resultant air velocity that the blade sees is dependent on the induced velocity and the local tip speed ratio:

$$Wu = \sqrt{Vu^2 [(TSR - \sin^2 \theta)^2 + (\cos^2 \theta)]} \quad (9)$$

Where, W_u is the resultant air velocity and TSR is the local tip speed ratio defined as:

$$TSR = R \frac{\omega}{Vu} \quad (10)$$

Where, R is the rotor radius and ω is the angular speed. The resultant air velocity is used then to determine the local Reynolds number of the blade.

$$Re_b = \frac{Wu c}{K_v} \quad (11)$$

Where Re_b is the local Reynolds number, c is the blade chord and K_v is the kinematic viscosity of the air, which has a reference value of $1.4607e-5$ [m²/s] for an air temperature of 15°C (Aerospacweb.org, 2005).

The equation for the angle of attack of the blade has been taken from Paraschivoiu (2002), the result has been demonstrated in order to ensure what is considered the 0° of the azimuth angle (θ) and also what is considered a negative angle of attack.

$$\alpha = \arcsin \left(\frac{\cos \theta \cos \alpha_0 - (X - \sin \theta) \sin \alpha_0}{\sqrt{[(TSR - \sin^2 \theta)^2 + (\cos^2 \theta)]}} \right) \quad (12)$$

Where, α is the angle of attack which is defined as the angle between the blade chord and the resultant air velocity vector. The previous equation allows the introduction of an initial angle of attack α_0 different from 0°. It considers positive angles of attack those which have the relative wind speed vector outside the rotor as in Figure 2, which occurs in the whole upstream half of the rotor.

Two different more intuitive formulas can be used to calculate the angle of attack at each blade position.

$$\alpha_{righthalf} = \arctan \left(\frac{Vu \cos \theta}{\omega R + Vu \sin \theta} \right)$$

$$\alpha_{lefthalf} = \arctan \left(\frac{Vu \cos \theta}{\omega R - Vu \sin \theta} \right) \quad (13) \ \& \ (14)$$

The local Reynolds number and the angle of attack are then used to find the corresponding lift and drag coefficients using double interpolation (i.e. one

interpolation for the Reynolds number and another for the angle of attack). The data tables had been extracted from Sheldahl and Klimas (1981).

The existing step between the two types of data has been considered a problem for a smoother simulated torque behavior, but a close analysis at the Reynolds number involved in the calculations for the design wind speed of 6 m/s has shown that the Reynolds ranges between 16·10⁴ (in green) and 36·10⁴ (in red) which have a smoother transition.

For the purpose of calculating the torque produced by the blade, the lift and drag forces are split in a blade trajectory tangential component and a normal component (radial). The normal and tangential coefficients can be calculated using:

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

$$C_t = C_l \sin \alpha - C_d \cos \alpha \quad (15) \ \& \ (16)$$

Where, C_n and C_t are the normal and tangential coefficients respectively and C_l and C_d are the lift and drag coefficients.

According to Paraschivoiu, using the blade element theory and the momentum equation, the upwind flow conditions can be characterized by f_{up} :

$$f_{up} = \frac{N c}{8 \pi R} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} |\sec \theta| (C_n \cos \theta - C_t \sin \theta) d\theta \quad (17)$$

Where, N is the number of blades. Then the interference factor can be obtained by:

$$au = \frac{\pi}{f_{up} + \pi} \quad (18)$$

For a given rotor geometry, rotational speed and free stream velocity, a first set of calculations from equations (6) to (18) is made using $au = 1$, then, with the new value of au the procedure is repeated until the initial and final au value are similar. This is repeated for each streamtube position and once the upstream induced velocities have been calculated, the downstream half is calculated using the same set of formulas, interchanging the upstream induced velocity V_u by the downstream induced velocity V_d (see equation (8)).

3.4 Rotor Torque and Performance

The tangential and normal forces as function of the azimuth angle θ are calculated the same way as lift and drag forces in an airfoil:

$$F_n(\theta) = \frac{1}{2} \rho c L W^2 C_n$$

$$F_t(\theta) = \frac{1}{2} \rho c L W^2 C_t \quad (19) \ \& \ (20)$$

Where, F_n and F_t are the normal and tangential force respectively, ρ is the air density [kg/m³], c is the blade chord [m], L is the blade length [m] and W is the relative wind speed.

The Torque produced by a blade is calculated using a combination between the Lift and Torque formulas.

$$Q(\theta) = \frac{1}{2} \rho c R L C_t W^2 \quad (21)$$

The average torque produced by the upstream half of the rotor (N/2 blades) is estimated averaging the contributions of each streamtube:

$$Q_{av} = \frac{N}{2\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} Q(\theta) d\theta \quad (22)$$

In order to work with non-dimensional magnitudes the average torque coefficient C_{qv} is calculated by:

$$C_{qv} = \frac{Q_{av}}{\frac{1}{2} \rho V_o^2 S R} \quad (23)$$

And finally the upstream half power coefficient C_{pu} is calculated with:

$$C_{pu} = C_{qv} X_t \quad (24)$$

Where, X_t is the rotor tip speed ratio which is calculated by:

$$X_t = \frac{R \omega}{V_o} \quad (25)$$

The average torque and power coefficient for the downstream half of the rotor are calculated using the same set of formulas from (21) to (24) using its corresponding values of tangential coefficient and induced velocities. The total power coefficient of the rotor is calculated then adding the two contributions:

$$C_{pt} = C_{pd} + C_{pu} \quad (26)$$

Where, C_{pt} and C_{pd} are the total and downstream power coefficients respectively.

4 MODEL LIMITATIONS

4.1 Stream tube Expansion Model

The double-multiple stream tube model does not account for expansion of the fluid as it losses velocity. A more realistic model considers the expansion of the stream tube affecting thus the interference factor calculation.

The significance of the stream tube expansion effects is greater as the tip speed ratio increases, being the difference between the power coefficients calculated with the stream tube expansion effect and without it less than 4% beyond a tip speed ratio of 8. The consideration of the expansion effects result in lower loads on the downwind half of the turbine (Paraschivoiu I, 2002, págs. 194-199).

As the tip speed ratio is designed to be below 3, the stream tube expansion effects will not be included in the calculation as its contribution to the accuracy of the results is not enough relevant.

4.2 Dynamic Stall

Dynamic stall is an unsteady aerodynamic effect that occurs at low tip speed ratios, due to quick and big variations of the angle of attack a vortex originates on the leading edge of the airfoil; this vortex produces higher lift, drag and pitching moment coefficients than those produced in static stall.

The MDSV code can be modified to include a model to compute these dynamic effects at low speed ratios. A description of the phenomenon as well as the dynamic-stall models that can be used can be found at (Paraschivoiu I., 2002).

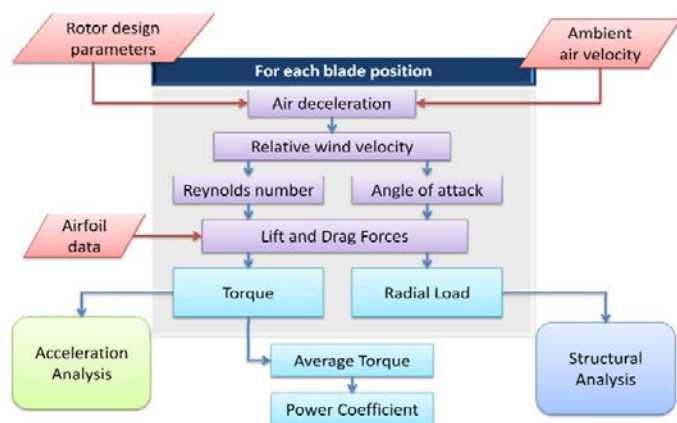
5 ALGORITHM IMPLEMENTATION

5.1 Algorithm Explanation

A Visual Basic Algorithm has been developed using above described procedure a reference to calculate the aerodynamic loads, torque and power coefficient. The algorithm has as Inputs the rotor design parameters and a set of tables containing the airfoil lift and drag coefficients depending on Reynolds number and angle of attack. For each stream tube it computes with iteration process the interference factor, relative wind velocity, Reynolds Number, angle of attack and tangential and normal forces.

The resulting torque and normal load (radial load) are used then for the acceleration and structural analysis respectively and the torque and power coefficient are obtained by integration of all the blade positions.

FIGURE 3
ALGORITHM FLOW CHART



The resulting torque and normal load (radial load) are used then for the acceleration and structural analysis respectively and the torque and power coefficient are obtained by integration of all the blade positions.

5.2 Number of Stream tubes Used

For the whole process, 36 stream tubes had been used, which means evaluating the wind conditions at blade positions in 5° increments. This number is the same used by the author of the procedure for presenting the results of his model (Paraschivoiu I. , 2002, p. 164).

A bigger number of stream tubes has been tested to evaluate the air conditions in smaller increments but the resulting power coefficient and torque doesn't present any variation.

6 ALGORITHM VALIDATION

The Mat lab Algorithm has been validated using the known results of one of the aerodynamic prediction models developed by I. Paraschivoiu. This model called CARDAAV considers the interference factor varying in function of the azimuth angle and also can consider secondary effects.

It should be noted that the reference data was taken reading a plot because the numeric results were unavailable, furthermore the code version CARDAAV which has been used to compute the reference plot consider secondary effects like the rotating tower and the presence of struts, which makes a difference in maximum power coefficient of 6% (Paraschivoiu I. , 2002, p. 185), the developed algorithm gives a difference in maximum Cp of 4.7%.

A comparison between the qualitative accuracy of the algorithm compared with the reference turbine give us a good approximation of the turbine performance at TSRs

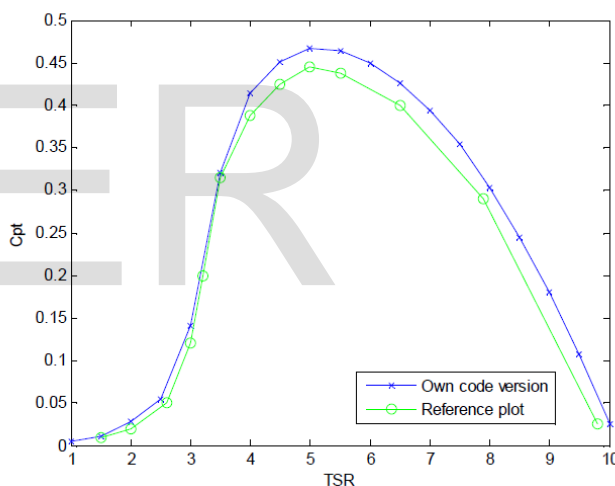
lower than 3.5, which will be the range of our turbine (see figure 5).

The reference turbine is found on (Paraschivoiu, Trifu, & Saeed, 2009) and its parameters are:

TABLE 2
ROTOR PARAMETERS FOR THE 7KW REFERENCE TURBINE
(PARASCHIVOU, TRIFU & SAEED, 2009)

Parameter	Value
Rotor diameter	6.0 m
Rotor height	6.0 m
Blade length	6.0 m
Blade chord (constant)	0.2 m
Blade airfoil	NACA0015
Number of blades	2
Rotor ground clearance	3 m

FIGURE 4
COMPARISON BETWEEN OWN CODE RESULTS AND THE CARDAAV CODE, DATA TAKEN FROM (PARASCHIVOU, TRIFU& SAEED, 2009)



The own version of the aerodynamic model takes into account a varying interference factor in function of the azimuth angle but doesn't consider the following effects that should improve the accuracy of the model:

- Presence of struts and mast.
- Vertical variation of the free stream velocity.
- Expansion of the stream tubes.
- Dynamic-stall effects.

A second validation with the results found from computational fluid dynamics and experimental analysis of a small wind turbine has been done in order to see the possible inaccuracy of the model for our design.

The second reference turbine is analyzed on (Raciti Castelli; Englaro; & Benini, 2011) and its parameters are:

TABLE 3
ROTOR PARAMETERS FOR THE SECOND REFERENCE TURBINE
(RACITI CASTELLI, ENGLARO & BENINI, 2011)

Parameter	Value
Rotor diameter	1.03 m
Blade length	1.4564 m
Blade chord (constant)	0.0858 m
Blade airfoil	NACA 0021
Number of blades	3

Despite these results, the momentum based model is still considered, a useful method. Different computational options, like CFD, are too time consuming to be considered for use within the scope of this thesis.

7 ROTOR DESIGN

7.1 Starting Parameters

A numerical optimization process of the design parameters have been done in order to select which could be the proper parameters for the intended application.

The optimization process has been carried out focusing on the effect each parameter has in the power coefficient and torque produced; the results are presented in plots.

In order to speed up the optimization process, some of the parameters have to be fixed for our purposes. The fixed parameters will be the design airspeed and the blade swept area.

The usual power coefficient values shown at the comparison with the competence turbines are between 0.15 and 0.2, so a swept area between 4 and 5.2 m² is needed to have 100W at 6 m/s. The selected swept area will be kept to 4m².

The design airspeed is kept at 6 m/s, because the purpose of the application is to take profit of the average wind speed rather than higher speeds, which are not so frequent.

The starting parameters and conditions in which the wind turbine has been tested are shown in table 4:

STARTING VALUES OF THE TURBINE PARAMETERS FOR THE OPTIMIZATION PROCESS

Symbol	Parameter	Starting value
V_0	Airspeed	6 m/s
TSR	Tip speed ratio	2
R	Rotor radius	1 m
c	Blade chord	0.3 m
L	Blade length	2 m
N	Number of blades	4
α_0	Initial angle of attack	0°

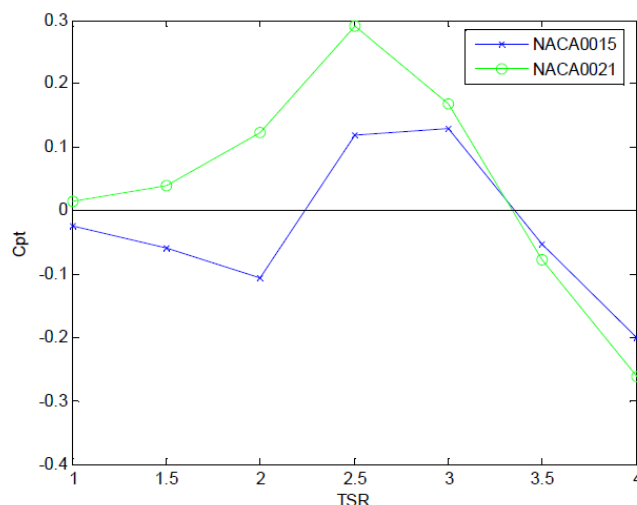
7.2 Aerofoil Selection

The airfoil has been selected considering the availability of airfoil data for angles of attack between -30 and 30° and the final thickness of the blade which is associated with its ability to withstand the loads.

The available airfoils with enough data to conduct the study of the aerodynamic loads and behavior of the wind turbine were available in a document issued by Sandia National Laboratories (Sheldahl & Klimas, 1981), this document provides the lift and drag coefficients depending on Reynolds number and angle of attack ranging from 0 to 180° for several NACA airfoils.

The selected airfoil is the NACA0021, which aerodynamics characteristics were determined using an airfoil property synthesizer code. This profile is one of the thickest available (21% of chord) and when compared with NACA0015 (thickness is 15% of chord) it can be seen that the self-starting behavior is improved with thicker airfoils (see Figure 5).

FIGURE 5
PERFORMANCE COMPARISON BETWEEN TWO DIFFERENT AIRFOILS



The actual shape of the NACA0021 airfoil can be found at (Abbott & Von Doenhoff, 1959, p. 335).

TABLE 4

The airfoil selection can be done using an airfoil simulation program like RFOIL, which according to (Claessens, 2006) can have problems to accurately predict the airfoil behavior at Reynolds numbers lower than 1·10⁶. Other alternative to wind tunnel testing are the two-dimensional computational fluid dynamics simulations.

7.3 Design Airspeed

A modification in the free stream velocity from 0 to 15 m/s varies the power coefficient significantly, beyond this airspeed the power coefficient remains constant at each tip speed ratio.

The torque behavior increases notably due to its quadratic dependence on airspeed.

The target performance is 100 W at 6 m/s, which should correspond to the rated wind speed, and therefore the maximum rpm of the turbine should be the corresponding to the optimum tip speed ratio of the turbine. But, in order to take advantage also of higher wind speeds, the rated wind speed will be set to 9 m/s but maintaining the initial performance target at 6 m/s.

The usual rated wind speed value ranges from 11.5 to 15 m/s, but a lower value may produce more energy overall because it will be more efficient at wind speeds between cut-in and rated.

7.4 Rotor Dimensions

The blade length and rotor radius have a major contribution in the torque behavior of the turbine as can be deduced from the torque equation. In general as bigger these parameters, bigger the torque produced. These parameters are involved also in the solidity calculation. The solidity becomes an important parameter when scaling down or up wind turbines and also determines the applicability of the momentum model.

The radius and blade variation analysis is done maintaining constant swept area. It can be seen in Figure 9 that an increase in rotor radius leads to greater maximum power coefficients, but they are achieved at greater tip speed ratios, so the little the radius, the less tip speed ratio is necessary to work at maximum power coefficient.

Coefficient is not affected by a sole variation of the blade length. This is deduced if the equation for calculating the power coefficient is developed and simplified (Equation 24), in this case the upwind power coefficient is illustrated, but the dependences are equal on the downstream half. We can see blade length is present both in the numerator and denominator of the equation.

$$C_{pu} = \frac{N c \omega \int_{\frac{\pi}{2}}^{\pi} C_t W^2 d\theta}{4 \pi V o^3} \quad (27)$$

The rotor radius R is simplified also from the equation but it is still implicit in the calculation of the relative velocity W, so we can state that the rotor radius have influence both in torque and power coefficient.

Nevertheless, the torque is affected by the blade length the same way the tangential force coefficient is dependent on the blade surface. Thus the blade length only affects torque and its optimization has to be done considering other factors as the swept area, which determines the power available from wind.

The blade tip losses are not contemplated in the model, in fact, one of the initial assumptions of the model is that there is no interaction between streamtubes, so in a real model, an increase on blade length should make the blade more efficient.

The optimization needs the input of a fourth factor, the maximum load due to both aerodynamic loads and rotational speed, as the radius will be the one determining them.

7.5 Solidity

Solidity is dependent on blade chord, number of blades and rotor radius; as radius effect has been already analyzed for constant swept area, the chord will be analyzed independently.

An increase in blade chord advances the TSR at which the maximum power coefficient is achieved, as bigger the chord, smaller the tip speed ratio. In order to reduce the centrifugal force, a big chord may be more effective than a lighter blade.

A bigger chord advances also the point of maximum torque, blades with smaller chords need a bigger tip speed ratio to develop maximum torque and it can affect the self-starting capabilities.

A better self-starting behavior will allow a smaller cut-in wind speed but will limit the maximum achievable power coefficient; the chord will be selected between 0.25 or 0.3 m depending on their acceleration behavior and structural limits.

The other parameter affecting solidity is the number of blades, keeping in mind the possible interference between blades and also a low solidity value, only three and four-bladed designs will be analyzed. Furthermore, the algorithm doesn't account for the wake turbulence that is

created behind each blade and can seriously affect the adjacent blade's lift and drag forces so a big number of blades may give too optimistic results.

As can be deduced from equations (17) and (18), a bigger number of blades lead to a bigger deceleration of the air, and this effect is greater than the increase in torque that can be produced having more blades

Three blades are more efficient than four for the same rotational speed; the final decision will be made considering the acceleration behavior, which will provide a better view of the self-starting characteristics.

7.6 Initial Angle of Attack

A positive initial angle of attack broadens the range of angular speed operation and a negative one shortens it; this is interesting when fixing the maximum rpm. Furthermore the torque is influenced the same way resulting in a lower maximum power coefficient and torque for negative angles of attack. The initial angle of attack for our design will be set at 0 degrees as the advantages of a different angle of attack are, according to this model, only evident at higher tip speed ratios than the intended for the model.

8 ACCELERATION ANALYSIS

An acceleration analysis has been performed in order to ensure the wind turbine will achieve the desired rpm. The first step is to make an estimation of the inertial momentum.

The rotor has been divided in N blades with two beams each, one on the bottom and one on the top. Approximating the form of the blade to cuboids and using the Steiner theorem, we have that the inertial moments are:

$$I_{blade} = \frac{1}{12} m_{blade}(c^2 + (0.21 c)^2) + m_{blade} R^2$$

$$I_{beam} = \frac{1}{12} m_{beam}(width^2 + R^2) + m_{blade} \left(\frac{R}{2}\right)^2 \quad (28) \ \& \ (29)$$

Where, "I" is for Inertia moment [kg m²] and m for mass [kg]. In order to calculate the mass of the wind turbine, Aluminium is used.

Multiplying the inertial momentum by the number of blades we have an approximate value of the total inertial momentum and we can calculate the angular acceleration:

$$\alpha = \frac{Q}{I} \quad (30)$$

Where, α is the angular acceleration [rad/s²], Q the torque [Nm] and I the rotor inertia moment [kg m²].

A qualitative acceleration analysis has been done (note that blades are approximated to cuboids) between a three-bladed rotor and a four-bladed rotor at a constant airspeed of 25 m/s in order to see if the diminution of inertia moment and different blade arrangement can improve the acceleration characteristics.

The four-bladed design has better behavior at low rpm, but the three bladed rotors present a much quicker response, which can be further improved using a lighter material and can be very useful to take profit from brief gusts. The four bladed rotors will not be further considered in the design.

9 STRUCTURAL ANALYSIS

A structural analysis will provide the limits of operation of the turbine, in terms of rotational speed, in order to prevent structural failure. The analysis is done as follows:

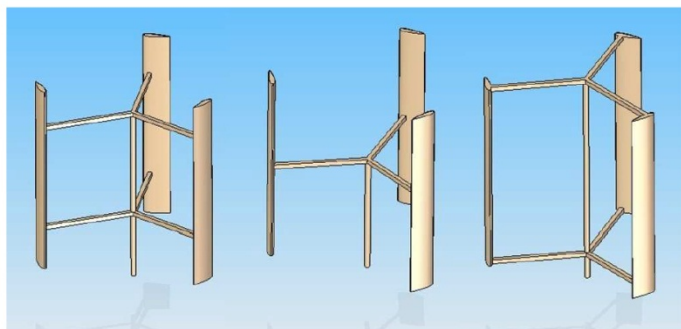
- A configuration of the wind structure is proposed.
- The maximum bending moment, normal and shear loads on a blade are analyzed.
- Consulting tables of mechanical properties of materials, the ultimate stress modules are found.
- The allowable stresses and loads are calculated using a safety factor.
- The moment of inertia of the blade shape is found using a CAD program.
- The numeric values of the allowable loads are calculated.
- A check is done to see if the turbine is able to accelerate to a point where the structural allowable limits can be surpassed.

9.1 Rotor Configuration

Three different rotor configurations (see figure 6) have been tested and are presented in the following figure, they have been numbered from left to right in order to refer them further in the analysis.

The first configuration attaches each blade by two points, which correspond to the Bessel points and minimize the maximum bending moment. These points are located at 20.7% of the blade length from each blade tip; a procedure for obtaining these points by static analysis can be found at (Saranpää, 2010).

FIGURE 6
ROTOR CONFIGURATIONS ANALYZED



The second and third configuration are equivalent in terms of maximum bending strength and shear strength, so the third rotor configuration is discarded as the second has lower exposed area per same strength, which will reduce the resulting drag associated with central mast and struts.

9.2 Allowable stress and selected materials

The allowable stress is defined as:

$$\text{Allowable stress} = \frac{\text{Yield or Ultimate strength}}{\text{Factor of safety}} \quad (31)$$

With a factor of safety bigger than 1 if the structure has to avoid failure. For, Aluminium yield strength is used.

The Yield Strength is dependent on the material used; in this design, the chosen material is Aluminium for blades, beams and mast.

Once the allowable stress is calculated, the allowable load is calculated with (Gere, 2004):

$$\text{Allowable_load} = \text{Area Allowable_stress} \quad (32)$$

We can appreciate a big difference in rotor strength between rotor configuration one and the others, second and third configurations are not further considered in the analysis as the limitation in maximum load relates directly with the maximum tip speed ratio and thus power coefficient.

9.3 Load Analysis

We can appreciate a big difference in rotor strength between rotor configuration one and the others, second and third configurations are not further considered in the analysis

The loads analyzed for the blade dimensioning are divided into centrifugal and aerodynamic loads. The

centrifugal force is dependent on both radius and the square of the rotational speed.

$$F_c = m R \omega^2 \quad (33)$$

Where, F_c is the centrifugal force [N], m is the blade mass [kg], R is the rotor radius [m] and ω the rotational speed [rad/s]. The normal force F_n is the aerodynamic load, an analysis of the resultant of the normal force and centrifugal force is made for one blade in a revolution. As they have equal direction, their resultant is:

$$F_r = F_c + F_n \quad (34)$$

Knowing the maximum allowable load for a given blade chord and a given material, the maximum rpm for each rotor construction can be found. The aerodynamic load is considered to be the load produced when the turbine achieves its

Cut out speed, which has been deduced from the average value and corresponds to 25 m/s.

The maximum allowable loads, as well as blade mass and maximum rpm are found on tables, we can establish the structural limit of the wind turbine at 580 rpm and 25 m/s wind speed regardless of blade material considering a blade chord of 0.28 m.

10 FINAL DESIGN AND OPERATION

With all the previous considerations, keeping in mind that a prototype must be built in order to validate the algorithm results and possibly make further refinements, the candidate for a prototype is presented on table 5.

10.1 Final Rotor Design Parameters

Using developed VB Program we decided the following dimensions and aluminium as a blade material.

BLADE DIMENSION

Length 80 cm

Chord 20.2 cm

Diameter 80 cm

Angle between Blades 60 Degrees

Initial Angle of Attack -30 Degrees

POLE DIMENSIONS

Length 82 cm

Diameter 4.2 cm

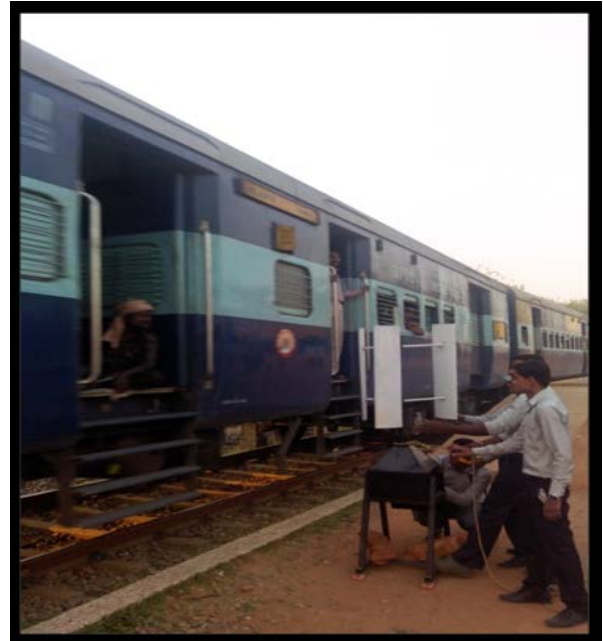
BASE DIMENSIONS

TABLE 5
 PRACTICAL READINGS FOR AIR VELOCITIES FOR VARIOUS

Sr. No.	Air Velocity (m/s)	Voltage (Volts)	Current (Amp)	Power (Watts)
1	5	3.52	8.63	30.44
2	4.8	3.3	8.63	28.48
3	3	2.1	8.6	18.06
4	4	2.9	8.63	24.89
5	5	3.71	8.6	31.91

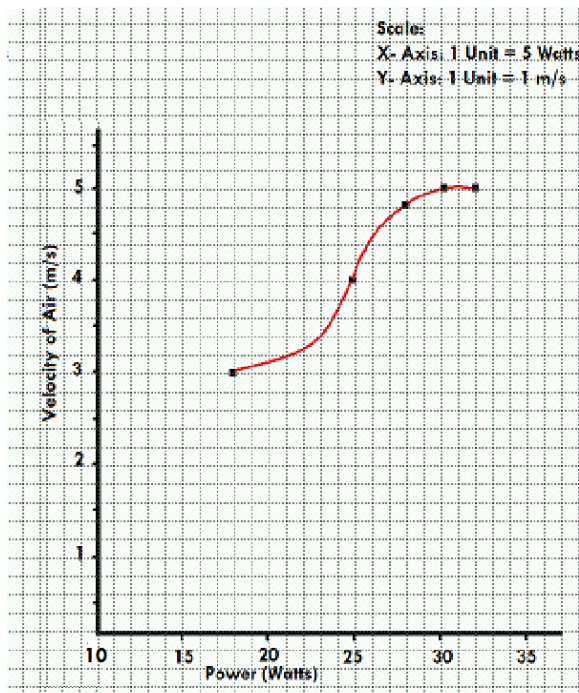
TRAINS

FIGURE 8
 PRACTICAL EXPERIMENTATION



10.2 Practical Experimentation

FIGURE 7
 GRAPHICAL REPRESENTATION

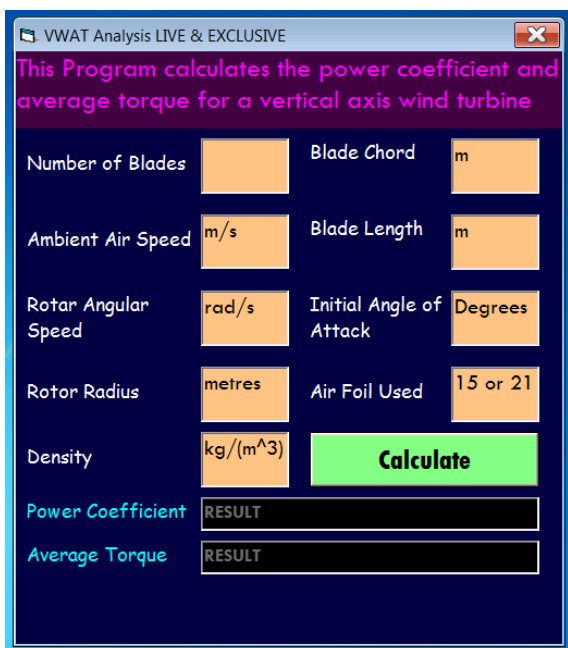


11 VISUAL BASIC APPLICATION DEVELOPMENT

11.1 PROGRAM DESCRIPTION

The purpose of this program is to provide the output torque and power coefficient using several input

FIGURE 9
 PROGRAM FORM (IN RUN MODE)



INITIAL ANGLE OF ATTACK	
DENSITY	
BLADE LENGTH	
ROTOR ANGULAR SPEED	

11.2 USER INSTRUCTIONS

The user will enter the input parameters in the corresponding in given units and further click on CALCULATE command button Then, further if the user wants to keep these calculations in the database he may click on the second command button which appears just after clicking the first command button.

11.3 DESIGN DOCUMENTATION

TABLE 6

INPUT	OUTPUT
NUMBER OF BLADES	AVERAGE TORQUE
AMBIENT AIR SPEED	POWER COEFFICIENT
ROTOR RADIUS	
BLADE CHORD	
AIR FOIL SERIES	

11.4 SAMPLE DATA

readings										
num	c	Vo	l	w	Ao	r	Rhow	Cp	Av_T	
3	0.2	2.5	0.8	6.28	-0.5	1028		-	106.4867	
					30			0.1040835	7708754	
								7355794		2
3	0.2	2.6	0.8	6.28	-0.5	1028		4.8745538	-	
					30			3165664E-02	56.09812	
									9027555	9
3	0.2	2.7	0.8	6.28	-0.5	1028		0.1706118	-	
					30			99219372	219.8842	
									2450192	8
3	0.2	2.8	0.8	6.28	-0.5	1028		0.2626192	-	
					30			84871486	377.4801	
									9494655	
3	0.2	2.9	0.8	6.28	-0.5	1028		0.3266542	-	
					30			33549858	521.6458	
									3852896	9
3	0.2	3.1	0.8	6.28	-0.5	1028		0.3830145	-	
					30			83964625	747.1260	
									0764809	3
3	0.2	3.2	0.8	6.28	-0.5	1028		0.3763923	-	
					30			74349001	807.5775	
									0520399	8
3	0.2	3.3	0.8	6.28	-0.5	1028		0.3759575	-	
					30			28028519	884.6552	
									6649262	3
3	0.2	3.4	0.8	6.28	-0.5	1028		0.3648899	-	
					30			04208637	939.0572	
									3014501	4
3	0.2	3.5	0.8	6.28	-0.5	1028		0.3560721	-	
					30			94806645	999.6216	
									5746498	6

readings									
num	c	Vo	l	w	Ao	r	Rhow	Cp	Av_T
3	0.2	3.6	0.8	6.28	-0.5	1028	0.3478507 45652505	1062.658 9472649	- 6
3	0.2	3.7	0.8	6.28	-0.5	1028	0.3146047 77979497	1043.431 5122246	- 7
3	0.2	3.8	0.8	6.28	-0.5	1028	0.2974786 86520048	1068.809 0127615	- 6
3	0.2	3.9	0.8	6.28	-0.5	1028	0.2650333 46069179	1029.408 6255433	- 8

11.5 DATA VALIDATION

Field Name: num
 Data Type: Number (Double)

Field Name: c
 Data Type: Number (Double)

Field Name: Vo
 Data Type: Number (Double)

Field Name: l
 Data Type: Number (Double)

Field Name: w
 Data Type: Number (Double)

Field Name: Ao
 Data Type: Number (Double)

Field Name: r
 Data Type: Number (Double)

Field Name: Rhow
 Data Type: Number (Double)

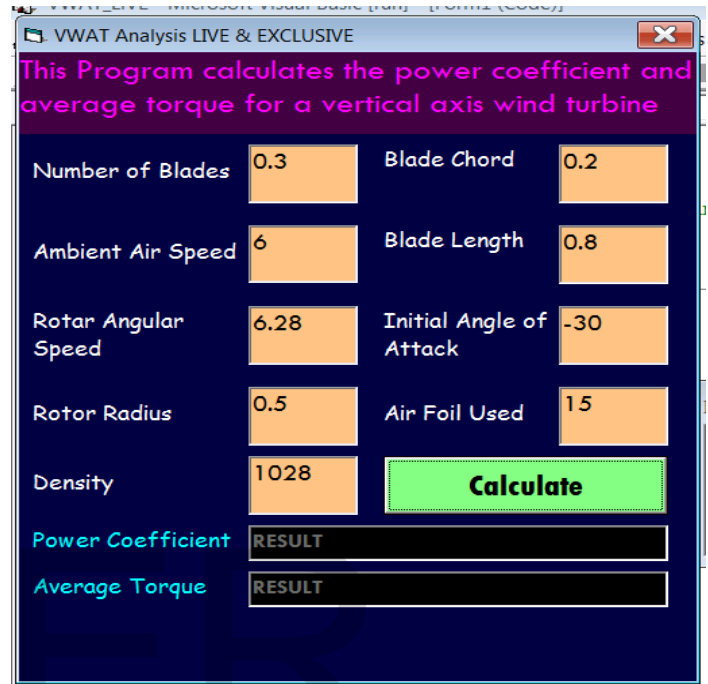
Field Name: Cp
 Data Type: Number (Double)

Field Name: Av_T
 Data Type: Number (Double)

11.6 SAMPLE PROJECT RUN

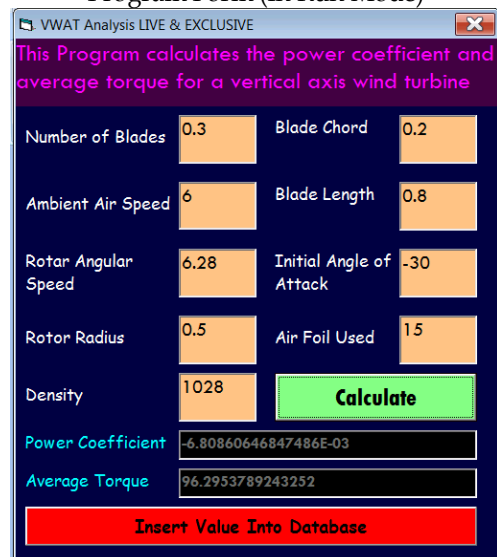
ADDING DATA IN FORM

FIGURE 10
 PROGRAM FORM (IN RUN MODE)



ADDING DATA INTO DATABASE

FIGURE 11
 Program Form (In Run Mode)



11.7 CODING

Dim d1 As New ADODB.Connection

End If

Dim r1 As ADODB.Recordset

If theta2 < 0 Then

Dim num_new As Double

theta2 = theta2 + 360

Dim c_new As Double

End If

Dim Vo_new As Double

Dim l_new As Double

thetad(st) = theta * pi / 180

Dim w_new As Double

thetad(st) = (theta2) * pi / 180

Dim Ao_new As Double

Dim r_new As Double

If theta - 360 < 0 Then

Dim Rhow_new As Double

theta = theta - 360 + (179 / 36)

Dim Cpt_new As Double

Else

Dim av_T_new As Double

theta = theta + (179 / 36)

Private Sub Command1_Click()

End If

Dim fup(36) As Double

Dim KV As Double

If theta2 - 360 < 0 Then

Dim Rho As Double

theta2 = theta2 - 360 - (179 / 36)

Dim nu As Double

Else

Dim S As Double

theta2 = theta2 - (179 / 36)

Dim Xt As Double

End If

n = 36

Next

pi = (22 / 7)

S = 2 * l.Text * r.Text

Dim thetau(36) As Double

Xt = w.Text * r.Text / Vo.Text

Dim thetad(36) As Double

KV = 0.000014607

Dim theta As Double

Rho = Val(Rhow.Text)

Dim theta2 As Double

Dim st As Double

theta = -90

'UPSTREAM CALCULATION

theta2 = -89

st = 1

Dim auvector(36) As Double

Dim auvectore(36) As Double

For st = 1 To 36

Dim fnu(36) As Double

Dim ftu(36) As Double

If theta < 0 Then

Dim tup(36) As Double

theta = theta + 360

Dim i As Double

Dim au As Double	$(\text{Cos}(\text{theta}(i)))^2)^{0.5}$	
Dim newau As Double	$\text{Reb} = \text{Wu} * c / \text{KV}$	'Blade
Dim Vu As Double	Reynolds number	
Dim x As Double		
Dim Wu As Double		'Cd = interp1 (A1,
Dim Reb As Double	Cd1, A, 'linear')	
Dim Costh As Double		
Dim cosao As Double	$\text{Costh} = \text{Cos}(\text{theta}(i))$	
Dim sinth As Double	$\text{cosao} = \text{Cos}(A_o)$	
Dim sinao As Double	$\text{sinth} = \text{Sin}(\text{theta}(i))$	
Dim A As Double	$\text{sinao} = \text{Sin}(A_o)$	
Dim cd As Double	$A = \text{Sin}((\text{Costh} * \text{cosao} - (x - \text{sinth}) * \text{sinao}) / ((x - \text{sinth})^2 + (\text{Costh}^2)^{0.5}))$	
Dim Cl As Double		
Dim neg As Double		
Dim cnu As Double	Select Case A	
Dim ctu As Double	Case 0 To 60	
Dim g As Double	cd = 0.5	
Dim actfup As Double	Cl = 0.5	
i = 0	Case 60 To 140	
'initialize the counter value	cd = (200 - 2 * Ao) / 80	
	Cl = (200 - 2 * Ao) / 80	
	Case 140 To 160	
While (i < n)	cd = (A - 173.33) / 26.66	
i = i + 1	Cl = (A - 173.33) / 26.66	
au = 1.01	Case 160 To 180	
induction factor upstream.	cd = (A - 180) / 80	
newau = 1	Cl = (A - 180) / 80	
initialize, au must be different from newau	End Select	
While ((au - newau) > 0.001)		
'Iterative process to find au	If ((A < 0) Then	
au = newau	A = -1 * A	
Vu = Vo * (au)	Cl = -1 * Cl	
=velocity upstream of wind turbine cylinder	End If	
x = (r.Text * w.Text / Vu)		' Cn = normal
'Local Tip speed ratio	coefficient, ' Ct = tangential coefficient	
Wu=local	cnu = Cl * Cos(A * pi / 180) + cd * Sin(A * pi / 180)	
resultant air velocity	'note that A is in degrees	
Wu = (Vu ^ 2 * ((x - Sin(theta(i))) ^ 2 +	ctu = Cl * Sin(A * pi / 180) - cd * Cos(A * pi / 180)	



```

' fup = function ' normal force coefficient
to find interference factor (au).          ftu(i) = (c.Text * l.Text / S) * ctu * (Wu / Vo.Text) ^ 2
'g=@(theta)                               ' tangential force coefficient
((abs(1/(sec      (theta))))*(Cnu*cos(theta)-   Ctu*      tup(i) = 0.5 * Rho * c.Text * r.Text * l.Text * ctu * Wu ^ 2
sin(theta))*(Wu/Vu)^2)                    ' torque produced in when the blade

' y = quadl(g, -89 * pi / 180, 89 * pi / 180)
crosses this streamtube
Wend
Dim av_tup As Double
Dim av_cqu As Double
Dim CpU As Double
av_tup_i = (1 / 3) * ((tup(1) + tup(36)) + 4 * (tup(3) + tup(5) +
tup(7) + tup(9) + tup(11) + tup(13) + tup(15) + tup(17) +
tup(19) + tup(21) + tup(23) + tup(25) + tup(27) + tup(29) +
tup(31) + tup(33) + tup(35)) + 2 * (tup(2) + tup(4) + tup(6) +
tup(8) + tup(10) + tup(12) + tup(14) + tup(16) + tup(18) +
tup(20) + tup(22) + tup(24) + tup(26) + tup(28) + tup(30) +
tup(32) + tup(34)))
av_tup = num.Text * av_tup_i / (2 * pi)
'upstream average torque
Average
torque coefficient
av_cqu = av_tup / (0.5 * Rho * S * r * Vo ^ 2)
CpU = av_cqu * Xt
'upstream power coefficient

'S1 = solve
('fup*newau*R = pi*(1-newau)*r(k)', 'newau')

newau = (pi / (actfup + pi))
'DOWNSTREAM CALCULATION
' new interference factor value for the next
iteration process.
Wend
auvector(i) = A ' Store
angle of attack value
auvectore(i) = newau Dim newad As Double
' Store au value in a vector
fnu(i) = (c.Text * l.Text / S) * cnu * (Wu / Vo.Text) ^ 2 j = n + 1
    
```

```

flag = 0
i = 0
'initialize the counter value

While (j > 1)
j = j - 1
i = i + 1
interference factor downstream.
ad = 1.01
velocity induction factor upstream.
newad = auvector(j) ^ 2 + (Costh ^ 2) ^ 0.5
' initialize, au must be different from newau

While ((ad - newad) > 0.001)
'Iterative process to find ad
ad = newad
ve = Vo * ((2 * auvector(j)) - 1)
'Ve = air velocity inside cylinder
vd = ve * ad
'Vd = air velocity downstream of cylinder
If vd > 0 Then
x = r * w / vd
Else
x = ve * 1.01
End If
'Local Tip speed ratio

' Wd=local resultant air velocity

Wd = (vd ^ 2 * ((x - Sin(thetad(i))) ^ 2 + (Cos(thetad(i))) ^ 2)) ^ 0.5
Reb = Wd * c / KV
' Reynolds number of the blade

(NACA = 15) Then
[A1, Cl1, Cd1] = NACAfinder15(Reb)

'Else
[A1, Cl1, Cd1] = NACAfinder21(Reb)

'End If
Costh = Cos(thetad(i))
cosao = Cos(Ao)
sinth = Sin(thetad(i))
sinao = Sin(Ao)
A2 = Sin((Costh * cosao - (x - sinth) * sinao) / ((x - sinth)
^ 2 + (Costh ^ 2) ^ 0.5)

neg = 0
If ((A2) < 0) Then
neg = 1
End If
A2 = Abs(A2) * 180 / pi
'Conversion to degrees to match table
Cl = interp1 (A1, Cl1, A, 'linear')
Cd = interp1 (A1, Cd1, A, 'linear')

Select Case A2
Case 0 To 60
cd = 0.5
Cl = 0.5
Case 60 To 140
cd = (200 - 2 * Ao) / 80
Cl = (200 - 2 * Ao) / 80
Case 140 To 160
cd = (Ao - 173.33) / 26.66
Cl = (Ao - 173.33) / 26.66
Case 160 To 180
cd = (Ao - 180) / 80
Cl = (Ao - 180) / 80
Case Else
MsgBox ("Enter proper value")
End Select
    
```


' S1 =

```

    If (neg = 1) Then
        A2 = -1 * A2
    End If

```

```

    'Restablish the original value for plots
    Cl = -1 * Cl

    End If

    ' Cn =
    normal coefficient, ' Ct = tangential coefficient
    Cnd = Cl * Cos(A2) + cd * Sin(A2)
    'note that A is in degrees
    Ctd = Cl * Sin(A2) - cd * Cos(A2)

```

```

'g=@(thetad) (abs(sec (thetad)).*(Cnd.*cos(thetad)-
    Dim fdw(20) As Double
    Dim g1 As Double

```

```

For g1 = 0 To 10
    fdw(g1) = ((Abs(1 / (Cos((-pi / 2) + (g1 * pi / 10))) ^ (-1))) *
    (cnu * Cos((-pi / 2) + (g1 * pi / 10)) - ctu * Sin((-pi / 2) + (g1 *
    pi / 10))))
Next g1

```

```

actfdw = (num.Text * c.Text / (8 * pi * r.Text)) * ((pi / 30) *
    ((fdw(0) + fdw(10)) + (4 * (fdw(1) + fdw(3) + fdw(5) + fdw(7)
    + fdw(9))) + 2 * (fdw(2) + fdw(4) + fdw(6) + fdw(8))))

```

```

quadr(g, 91 * pi / 180, 269 * pi / 180)
'y =
'fdw
= n * c * y / (8 * pi * r)

```

```

[newau] = solve ('fup*newau = pi*(1-newau)')

```

'MATLAB ALGORITHM APPENDIX 5: 6(7)

newau

```

solve ('fup*newau*R = pi*(1-newau)*r(k)', 'newau')
    If (flag = 0) Then
        newadw = pi / (actfdw + pi)
    End If

```

```

'if the iteration process does not converge, the value of the
    Dim advector(36) As Double
    Dim advectore(36) As Double
    Dim ftd(36) As Double
    Dim fnd(36) As Double
    Dim Tdw(36) As Double

```

'interference factor upstream from the same streamtube is taken

```

    If (newad < 0.01) Then
        If (i > 1) Then
            newad = advector(i - 1)
        Else
            newad = auvector(i)
        End If
        flag = 1
    End If
Wend

```

```

    advector(i) = A2
    advector(i) = newad

```

'Store ad value in a vector

```

' Force coefficients and torque calculation
    fnd(i) = (c * l / S) * Cnd * (Wd / Vo) ^ 2
    ftd(i) = (c * l / S) * Ctd * (Wd / Vo) ^ 2
    Tdw(i) = 0.5 * Rho * c * r * l * Ctd * Wd ^ 2
Wend

```

```

'ts4 = f_trapezoidal_integration_s(thetad, Tdw)

```

```

'syms 'av_Tdw = n * (ts4) / (2 * pi) ' downstream average torque
av_tdw_i = (1 / 3) * ((Tdw(1) + Tdw(36)) + 4 * (Tdw(3) +

```

Tdw(5) + Tdw(7) + Tdw(9) + Tdw(11) + Tdw(13) + Tdw(15) +
 Tdw(17) + Tdw(19) + Tdw(21) + Tdw(23) + Tdw(25) +
 Tdw(27) + Tdw(29) + Tdw(31) + Tdw(33) + Tdw(35)) + 2 *
 (Tdw(2) + Tdw(4) + Tdw(6) + Tdw(8) + Tdw(10) + Tdw(12) +
 Tdw(14) + Tdw(16) + Tdw(18) + Tdw(20) + Tdw(22) +
 Tdw(24) + Tdw(26) + Tdw(28) + Tdw(30) + Tdw(32) +
 Tdw(34)))

av_Tuw = num.Text * av_tdw_i / (2 * pi) 'upstream average
 torque

Average
 torque coefficient

CpU = av_cqu * Xt

av_cqd = av_Tuw / (0.5 * Rho * S * r * Vo ^ 2)

cpd = av_cqd * Xt

If (cpd + CpU) > -0.5 And (cpd + CpU) < 0.5 Then

Cpt.Text = cpd + CpU ' Total
 power coefficient

Else

Cpt.Text = cpd + CpU

MsgBox ("Improper Input")

End If

av_T.Text = -(av_Tuw + av_tup)

Command2.Visible = True

num_new = num.Text

c_new = c.Text

Vo_new = Vo.Text

l_new = l.Text

w_new = w.Text

Ao_new = Ao.Text

r_new = r.Text

Rhow_new = Rhow.Text

Cpt_new = Cpt.Text

av_T_new = av_T.Text

End Sub

Private Sub Command2_Click()

Set d1 = New ADODB.Connection

d1.Open "project_connection"

d1.Execute "insert into table1(rollno, first_name) values
 (Rho, c_new)"

d1.Execute "insert into readings(num, c, Vo, l, w, Ao, r,
 Rhow, Cp, Av_T) values (" & num_new & ", " & c_new & ",
 " & Vo_new & ", " & l_new & ", " & w_new & ", " & Ao_new
 & ", " & r_new & ", " & Rhow_new & ", " & Cpt_new & ", " &
 av_T_new & ")"

Command2.Visible = False

End Sub

Private Sub Cpt_Gotfocus()

Cpt.Text = ""

End Sub

Private Sub Form_Load()

Command2.Visible = False

num.Text = ""

r.Text = "metres"

w.Text = "rad/s"

Vo.Text = "m/s"

c.Text = "m"

l.Text = "m"

Ao.Text = "Degrees"

Rhow.Text = "kg/(m^3)"

NACA.Text = "15 or 21"

av_T.Text = "RESULT"

Cpt.Text = "RESULT"

End Sub

Private Sub l_GotFocus()

l.Text = ""

End Sub

Private Sub num_Gotfocus()

```
num.Text = ""
```

```
End Sub
```

```
Private Sub NACA_Gotfocus()
```

```
    NACA.Text = ""
```

```
End Sub
```

```
Private Sub r_Gotfocus()
```

```
    r.Text = ""
```

```
End Sub
```

```
Private Sub Rhow_Gotfocus()
```

```
    Rhow.Text = ""
```

```
End Sub
```

```
Private Sub Vo_Gotfocus()
```

```
    Vo.Text = ""
```

```
End Sub
```

```
Private Sub w_Gotfocus()
```

```
    w.Text = ""
```

```
End Sub
```

```
Private Sub Ao_Gotfocus()
```

```
    Ao.Text = ""
```

```
End Sub
```

```
Private Sub av_T_Gotfocus()
```

```
    av_T.Text = ""
```

```
End Sub
```

```
Private Sub c_Gotfocus()
```

```
    c.Text = ""
```

```
End Sub
```

```
'Set r1 = New ADODB.Recordset
```

```
'Set r2 = New ADODB.Recordset
```

```
'r1.Open "select *from readings", d1, 3, 3
```

```
'r2.Open "Select * from readings", d1, 3, 3
```

```
'Text1 = r1("blade_chord")
```

```
'Text1 = r2("blade_chord")
```

```
'd1.Execute "insert into table1(rollno,first_name) values  
(1,'tanmay mone)'"
```

12 CONCLUSION

Aluminium is a suitable material for blade construction in small-scale wind turbines and the construction of an affordable wind turbine with common workshop tools can be contemplated.

The power developed is directly proportional to air turbulence.

A three-bladed design is more efficient than a four-bladed rotor; a low solidity wind turbine may present self-starting problems as rotor efficiency is poor at low tip speed ratios.

There is an optimum turbine rotational speed for each ambient wind speed at which the maximum efficiency is achieved. The energy production of a fixedpitch wind turbine can be improved adjusting the rated airspeed to the place of installation average wind conditions in order to reach its maximum efficiency.

Larger radius turbines are more efficient than small turbines at same rotational speed as the tangential airspeed increase leads to smaller angles of attack, bigger Reynolds numbers and thus bigger blade lift coefficients. Experimental tests are needed in order to refine the design and validate the aerodynamic model used.

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