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Design and Experimental Analysis of a 200W Micro Wind Turbine

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Abstract

Majority of the regions in India are characterized by moderate and low wind regimes. These regions have variable and gusty winds. Our low-wind energy turbine addresses this problem and is capable of providing power to millions of people not connected to the grid in low wind conditions.
Our objective is to design a suitable wind turbine applicable in low speed regions extracting maximum power output. Our team aims to take on the challenge of improving wind turbine efficiencies, at low to medium wind speeds, to reduce environmental impact and encourage adoption of wind energy at domestic and commercial building rooftops and small distributed systems.
Blade Element Momentum theory was adopted to find the suitable parameters at the required wind speeds. Tools like Q-Blade and X-foil were used to optimize the CAD model of the blade.
A customized Wind tunnel was fabricated by the team to validate the practical results against the theoretical ones. Rapid Prototyping technique of 3-D printing was used to manufacture the blades.
Final results establish a close relationship between the theoretical and experimental values.

1. Introduction

For the solar and wind industries of the world, it has been a long-held dream: to produce energy at a cost equal to conventional sources like coal and natural gas.
With humongous subsidies being provided by government agencies like the United States Environment Protection Agency (USEPA) and in India's context the Ministry of New and Renewable Energy (MNRE) to implement such technologies, and projects being done by technical institutions like IEEE and The Energy and Resources Institute (TERI), that dream appears to be coming close to reality. The global energy sector is experiencing a push towards the adoption of renewable energy generation over conventional sources.
Now that we're reaching a point where we can compete with conventional sources of energy, it is becoming increasingly important to not just pit unconventional sources of energy against conventional sources of energy, but also to pit one renewable source of energy against another.
In present times, the debate is largely whether to choose Solar PV over Wind or the other way round. The present trend, very rightly, is to have a resource assessment study done at a particular place, and use solar or wind depending on which is more economical to set up. But in doing so, one important factor is left out, i.e. the relative environmental impact of each technology.
Our aim is to increase the penetration of small and distributed wind. Majority of the small rooftop turbines presently used in India are imported and are designed for high wind regimes. Hence in Indian conditions these have a high cut-in wind speed and poor low wind performance.

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This calls for an indigenously designed small wind turbine with optimal low wind performance and the ability to capture gust energy. Gusts are typically short blasts of wind which blow for a very short period of time. Capturing this energy calls for high starting torque and low rotational inertia so that the rotor blades of the turbine can respond quickly to the fluctuations in wind. [1]
Optimizing each technology is a challenge in its own. Our team aims to take on the second challenge of improving wind turbine efficiencies, at low to medium wind speeds, to reduce environmental impact and encourage adoption of wind energy at domestic and commercial building rooftops and small distributed systems.
This paper is divided into 3 sections:

- Blade Element Momentum Review
- Design of the Blade
- Experimental Results

2. Blade Element Momentum Review

Blade element momentum (BEM) theory is one of the oldest and most commonly used methods for calculating induced velocities on wind turbine blades. This theory actually originates from two different theories: blade element theory and momentum theory.
Blade element theory [2] assumes that blades can be divided into small elements that act independently of surrounding elements and operate aerodynamically as two-dimensional airfoils whose aerodynamic forces can be calculated based on the local flow conditions. These elemental forces are summed along the span of the blade to calculate the total forces and moments exerted on the turbine.
The momentum theory [3] assumes that the loss of pressure or momentum in the rotor plane is caused by the work done by the airflow passing through the rotor plane on the blade elements. Using the momentum theory, one can calculate

the induced velocities from the momentum lost in the flow in the axial and tangential directions. These induced velocities affect the inflow in the rotor plane and therefore also affect the forces calculated by blade element theory. This coupling of two theories ties together blade element momentum theory and sets up an iterative process to determine the aerodynamic forces and also the induced velocities near the rotor.

In practice, BEM theory is implemented by breaking the blades of a wind turbine into many elements along the span. As these elements rotate in the rotor plane, they trace out annular regions, across which the momentum balance takes place. These annular regions are also where the induced velocities from the wake change the local flow velocity at the rotor plane. BEM can also be used to analyze stream tubes through the rotor disk, which can be smaller than the annular regions and provide more computational fidelity.

The generation of rotational kinetic energy in the wake results in less energy extraction bythe rotor than would be expected without wake rotation. In general, the extra kinetic energy inwind turbine wake will be higher if the generated torque is higher. Thus, as will be shownhere, slow-running wind turbines (with a low rotational speed and a high torque) experiencemore wake rotation losses than high-speed wind machines with low torque.

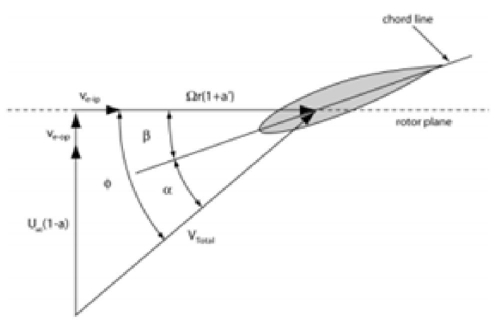

Fig 1: Local Elemental Velocities

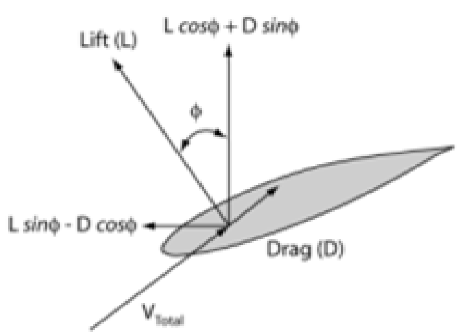

Fig 2: Local Elemental Forces

As we are required to obtain the angle of attack to determine the aerodynamic forces on an element, we must first determine the inflow angle based on the two components of the local velocity vector. Assuming that the blade motion is very small, the resulting equation is dependent on the induced velocities in both the axial and tangential directions as well as the local tip speed r_a

$$tan\phi = \frac{U_\infty(1-a)}{\Omega r(1+a')} = \frac{1-a}{(1+a')\lambda_r} \qquad [1]$$

However, if the blade motion is significant we must include the local velocities in the calculation of the inflow angle, as follows:

$$tan\phi = \frac{U_\infty(1-a)+v_{e-op}}{\Omega r(1+a')+v_{e-ip}} \qquad [2]$$

This equation holds for all elements of the blade along the span, although typically the inflow angle changes with element location. The induced velocity components in Equations 1 and 2 are a function of the forces on the blades and we use BEM theory to calculate them. A thorough derivation of these equations can be found in most wind turbine design handbooks. From blade element theory, the thrust distributed around an annulus of width dr is equivalent to

$$dT = B\frac{1}{2}\rho V_{total}^2(C_l\cos\phi + C_d\sin\phi)cdr \qquad [3]$$

and the torque produced by the blade elements in the annulus is equivalent to

$$dQ = B\frac{1}{2}\rho V_{total}^2(C_l\sin\phi - C_d cos\phi)crdr \qquad [4]$$

Now, to relate the induced velocities in the rotor plane to the elemental forces of equations, we must incorporate the momentum part of the theory, which states that the thrust extracted by each rotor annulus is equivalent to

$$dT = 4\,\pi r\rho U_\infty^2(1-a)adr \qquad [5]$$

and the torque extracted from each annular section is equivalent to

$$dQ = 4\pi r^3\rho U_\infty\Omega(1-a)a'dr \qquad [6]$$

Thus, when we include two-dimensional airfoil tables of lift and drag coefficient as a function of the angle of attack, α, we have a set of equations that can be iteratively solved for the induced velocities and the forces on each blade element. However, before we solve our system of equations, we would like to take into account several corrections to the BEM theory. These corrections include tip- and hub-loss models to account for vortices shed at these locations, the Glauert correction to account for large induced velocities (a >0.4), and the skewed wake correction to model the effects of incoming flow that is not perpendicular to the rotor plane.

3.1 Design of the blade

NACA 22112 [3] was chosen for a few prominent reasons. The large relative thickness can accommodate the root tube easier than thinner profiles. Initial profiles should have a high cross-sectional stiffness to limit overall blade weight and tip deflection. The in board profiles should maximize lift while having a high lift-drag ratio is of less importance [4]. In other words, the inboard profiles, which are the profiles that are closer tothe root, are chosen based on a structural design requirement while trading off optimum aerodynamic properties. The relative large thickness of the airfoil allows these requirements to be met.

3.2: Chord and Twist Distribution

Airfoil data after being generated from XFOIL was fed into a BEM analysis program called Q Blade which utilizes the Blade Element Momentum theory to generate optimal

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distributions of chord and twist distribution. [5]Often these values are not practical enough to manufacture, hence the program allows you to modify these values to a manufacture able scale and then give you the performance analysis due to modifications done. The two figures below compare the values of optimal, fitted and practical distributions of chord and twist.

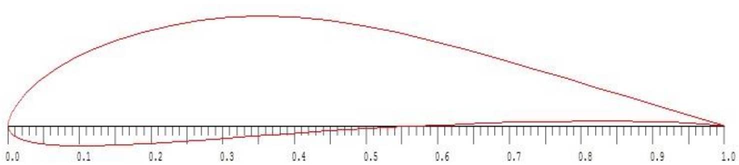
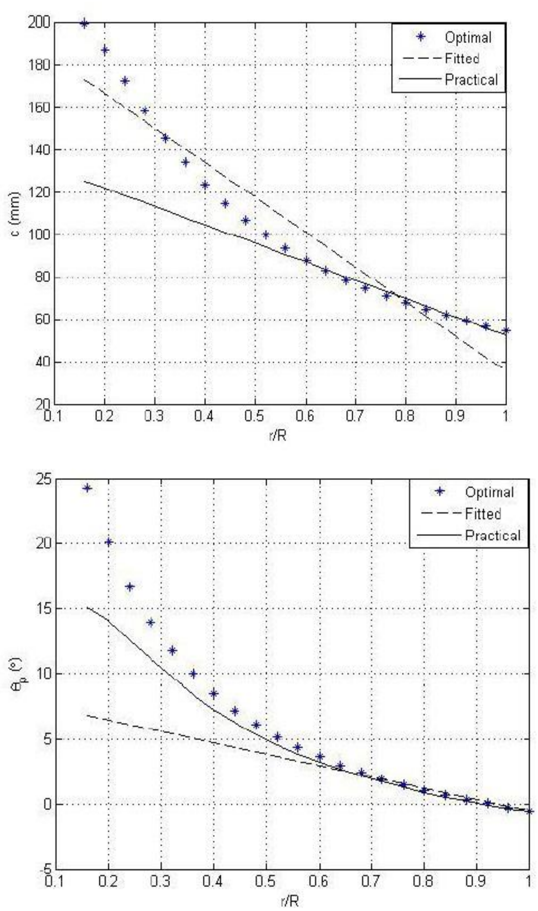


Fig. 2.1 design of Blade



Graph 1*:* Values of Chord and Twist

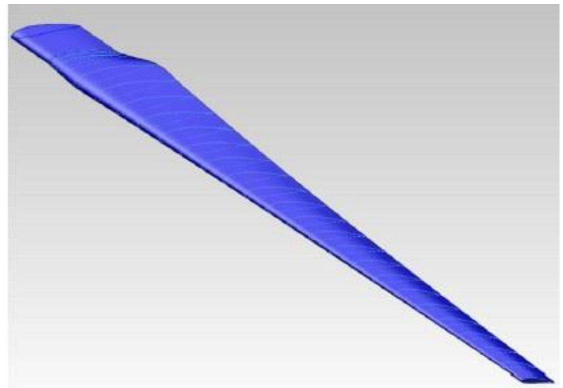
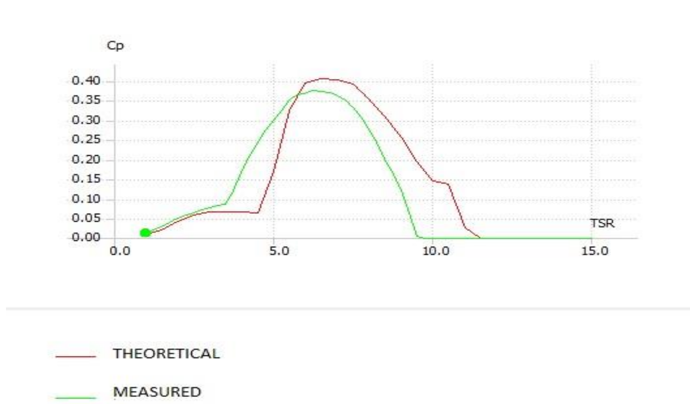


Fig 3: Complete CAD Model of Blade

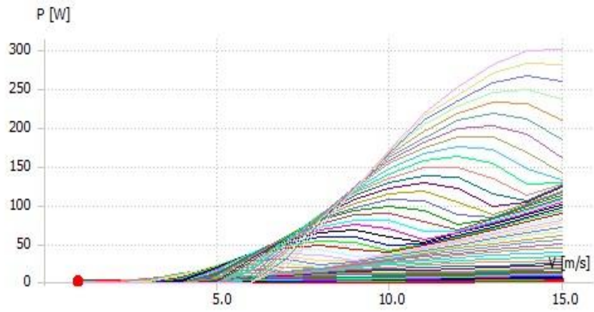
4 Results

The results are summarized below in the form of comparison between theoretical and measured values of the blade values. The results were obtained on a custom designed wind tunnel with a test section of 1mx1m and maximum air velocity of 14m/s.

Fig 4: 3-D Printed Blades in wind tunnel

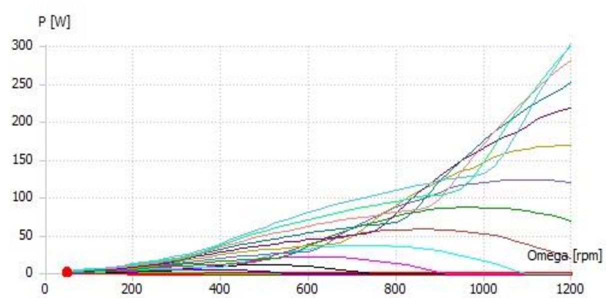


Graph 2: Comparison between theoretical and experimental values of Cp



Graph 3: Experimental Power vs. Velocity

The simulated power coefficient curve is not very smooth at some points, especially in the tip speed ratio range of 5 to 6. There must be a trade-off between these two opposing influences that results in an overall reasonable power output. The method of calculating wake factor influences in the BEM simulation has a noticeable impact on the results.



Graph 4: Experimental Power vs. RPM

The BEM process includes iterative solving of sets of equations. The numerical stability of the iteration process depends on the properties of the lift and drag coefficient functions. For this blade, angle of attack along the span varies significantly, and plays a very important role. When local angle of attack is around stall point or becomes negative, getting the BEM code toconverge can become difficult. Sometimes the local power coefficient close to the tip becomes negative.

5 Conclusions

NACA 2212 can accommodate the root tube easier than thinner profiles due to its large relative thickness and hence is a good choice for use as an initial profile.

Buhl method was found to be better than the Glauert and Wilson-Walker methods for calculating the wake factor for the case of this turbine.

The simulated power coefficient curve is not very smooth at some points, especially in the tip speed ratio range of 5 to 6. This is because when the tip speed ratio increases, the local power coefficient at the tip will decrease and local power coefficient close to the root increases.

The differences in the observed and theoretical values of power were found to be within acceptable limits.

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