Vertical Axis Micro Wind Turbine Design for Low Tip Speed Ratios

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ABSTRACT

A small-scale vertical axis wind turbine (VAWT) is developed for use in areas lacking adequate energy infrastructure; the materials and methods of construction are selected to minimize cost as much as possible. In order to overcome the self-starting issues associated with VAWTs and low tip speed ratios, solutions such as high solidity, guide vanes, and drag tubes are considered. A computer simulation is written to predict the performance of turbines incorporating these features, and the trends are compared to those from the literature. The mechanics and feasibility of drive systems using motor-generators and bicycles are also examined.

Keywords: Design, Model, Multiple Streamtube Theory, Simulation, VAWT, and Vertical Axis Wind Turbine.

NOMENCLATURE

A_t	swept area
c	chord
c_d	section drag coefficient
c_l	section lift coefficient
C_P	power coefficient
C_t	tangential coefficient
h	height
N	number of teeth
N_b	number of blades
P	power
r	radius
Re	Reynolds number
T	torque
U_t	tangential velocity
U_∞ or V	freestream velocity
α_b	blade angle of attack
β_b	blade inclination from horizontal
θ	angular position
θ_b	blade azimuth angle
λ	tip speed ratio
ρ	density
σ	solidity
ω	angular velocity

1 INTRODUCTION

In recent years there has been a large push toward clean sources of energy; this in conjunction with the advent of the "smart grid" has created an incentive to develop renewable energy technologies scaled for single households. However, these concepts have also found favor in developing nations and areas otherwise detached from an electric grid due to their small scale and autonomy. In particular, vertical axis wind turbines present one promising option and have a number of advantages over the traditional horizontal axis wind turbine. For example, they operate the same regardless of wind direction, and they can be located closer to the ground for easier maintenance. Furthermore, the blades do not require any twist and thus are simpler to manufacture. On the other hand, VAWTs tend to have "dead zones" where the orientation of the blades causes cancellation of forces in the tangential direction, meaning there is no net torque. These are especially an issue when a turbine operates at low tip speed ratios, since it may not be spinning fast enough to escape them. The tip speed ratio λ is the blade tangential velocity divided by the freestream velocity, as shown in Eq. (1):

$$\lambda = \frac{U_t}{U_\infty} = \frac{r\omega}{U_\infty} \tag{1}$$

To prevent the turbine from becoming stuck in these dead zones, it is advantageous to increase the overall torque. Then, if the turbine has sufficient momentum, it will be able to spin through the short bands where the net torque is zero [4]. Guide vanes can be used to change the angle of attack seen by a blade at strategic points along its revolution. By modifying the angle of attack, the tangential force coefficient and consequently net torque can again be increased. In addition, drag tubes may be helpful in starting the turbine when wind speeds are low: Since they are capable of producing a high starting torque, they can accelerate the turbine until the blades take over in providing most of the torque.

Kirke [4] notes that "[s]elf-starting problems can be overcome electrically if the load is a synchronous alternator or a DC generator which can function as a motor and can be used to drive the turbine up to operating speed," although this is more common in grid-connected wind turbines than micro VAWTs. Nonetheless, motor-generators remain a viable option for tackling the self-starting issue and can be replaced with other forms of energy addition, such as a pedal-powered system.

2 CONSTRUCTION

The Georgia Tech VAWT is a scaled-up version of models built by the Experimental Aerodynamics Group and has a diameter of 6 ft. Like previous iterations, it has three arms, each with a pair of straight blades. Those parts which rotate are constructed from aluminum in order to reduce loading on the arms, but the static frame has been built out of steel so as to keep costs low.

The design and construction of the blades are also integral to building a vertical axis wind turbine. The blades should be light and easy to make yet strong enough to withstand high winds. In order to meet these criteria, the blades of the Georgia Tech VAWT have a fiberglass skin and spars as well as foam ribs due to these materials' strength and low weight. Epoxy resin was used to bond the skin, spars, and ribs to each other as is common in the manufacture of composite blades. In choosing an airfoil, a NACA 0015 was decided upon due to its symmetry and widespread use.

3 SIMULATION

To assist in the initial sizing of a vertical axis wind turbine, a simulation based on Strickland's multiple streamtube theory [6] was written. In multiple streamtube theory, the turbine is split into several streamtubes along the horizontal and vertical axes. The streamwise forces on the blade elements are equated to the changes in fluid momentum, and an induction factor is found for each streamtube which describes how the blades slow the air moving through the turbine. A local power coefficient is then computed based on Eq. (2) for each streamtube; these are averaged to determine the overall power coefficient of the turbine. The numerator represents the power produced by the turbine, whereas the denominator represents the total wind power available to the turbine.

$$C_P = \frac{P}{\frac{1}{2}\rho A_t U_\infty^3} \tag{2}$$

In addition to simply providing the user with a power curve for a given set of dimensions, the simulation gives insight into how changing these parameters can affect turbine efficiency. Though much of the code is adapted from Strickland's DARrieus Turbine (DART) model [6], it is also capable of incorporating the effects of straight blades, variations in Reynolds number, and drag tubes.

Figure 1 shows that for a turbine with curved NACA 0012 blades and a solidity of 0.27, the simulation is in good agreement with Sandia's performance predictions [6]. Similarly, Figure 2 overlays the Georgia Tech performance predictions onto Sandia's performance predictions for a turbine with a solidity of 0.18. The simulation uses the same airfoil data as Sandia's code (that from Jacobs and Sherman [3]); nonetheless, it slightly overpredicts the power coefficient at low tip speed ratios and underpredicts it at higher tip speed ratios. When Reynolds number effects are taken into account, the power coefficient drops as expected: The actual Reynolds number values are for the most part lower than that assumed for the blue curve, so aerodynamic stall would occur earlier [6]. However, the simulation also tends to underpredict the power coefficient when incorporating Reynolds number effects.

The gaps in the green curve result from a lack of available airfoil data at Reynolds numbers below 10,000. These lift and drag coefficients were obtained from Sheldahl and Klimas [5] and at present appear to be the most comprehensive compilation of airfoil data ranging over different Reynolds numbers. However, as not all of this data was obtained experimentally—coefficients at Reynolds numbers below 360,000 were

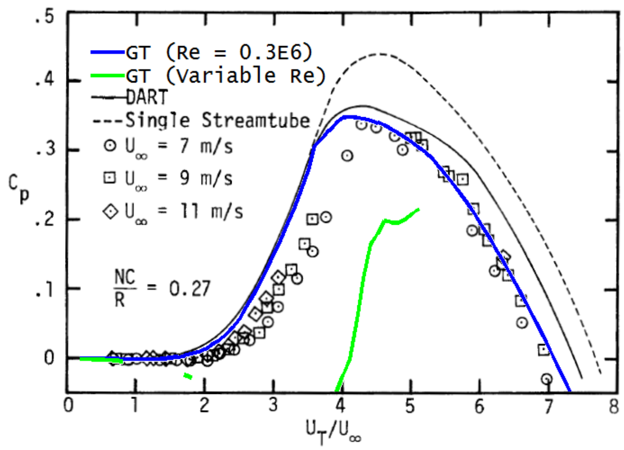

Figure 1: Comparison of Georgia Tech and Sandia performance predictions at a solidity of 0.27.

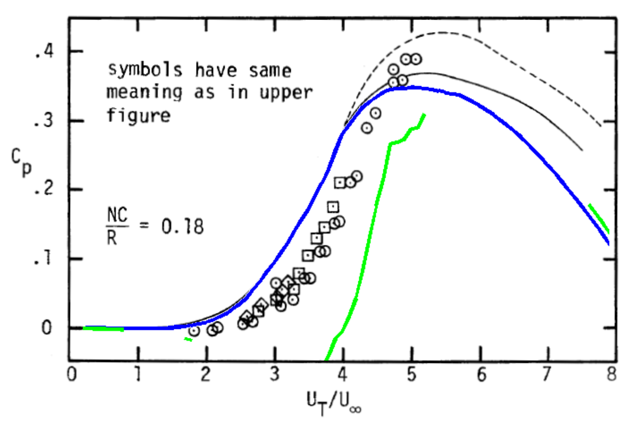

Figure 2: Comparison of Georgia Tech and Sandia performance predictions at a solidity of 0.18.

extrapolated by Sheldahl and Klimas using their own computer program—there are several errors which call into question the validity of the data. In particular, some sets of data for lower Reynolds numbers give a negative lift coefficient at the dip after stall. In any case, Kirke [4] states the "discrepancies between [Jacob's and Sheldahl's] data for the same section under supposedly similar conditions show that it is dangerous to look for trends by comparing the performance of different aerofoil sections at low Re using data from different sources."

Solidity Effects

One extremely important parameter for self-starting is the solidity σ, a measure of the volume being swept by the rotor. This value is calculated as shown in Eq. (3):

$$\sigma = \frac{N_b c}{r} \tag{3}$$

By adjusting the number of blades, chord length, and radius in the graphical user interface, one can see that increasing the solidity pushes the maximum power coefficient to lower tip speed ratios (Figure 3). This is desirable in the case of VAWTs, which often operate at angular velocities lower than those of horizontal axis wind turbines. On the other hand, the plot suggests that increasing solidity too much not only causes the maximum power coefficient to drop but also causes the power curve to have a sharper peak, meaning the turbine efficiency is more sensitive to changes in wind speed. Nonetheless, Templin [7] states, "Although lower values of solidity may widen the useful operating range of the turbine, in terms of the velocity ratio $R\omega/V$, they also reduce maximum available power. Blade centrifugal stresses, will also tend to increase at low solidity, because of the high rotational speeds."

Figure 3 applies to straight-bladed VAWTs using NACA 0015 airfoils, similar to the one built by Georgia Tech. Strickland's DART code has been modified to allow for straight blades by changing the variable β_b in Eq. (4) to a constant $\frac{\pi}{2}$ rad. Here β_b is the angle of a blade segment with respect to the horizontal, h is the height of the blade segment, r is the local radius, and θ_b is the azimuth angle.

$$\beta_b = \tan^{-1} \frac{\Delta h}{r \Delta\theta_b \sin\theta_b} \tag{4}$$

Comparing Figures 1 and 2 to Figure 3, it is interesting to note that the power curves for the straight-bladed VAWT are generally sharper than those for a turbine with curved blades.

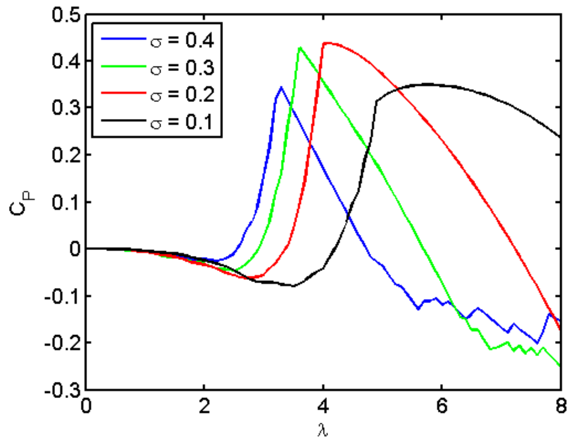

Figure 3: Power coefficient vs. tip speed ratio for various solidities.

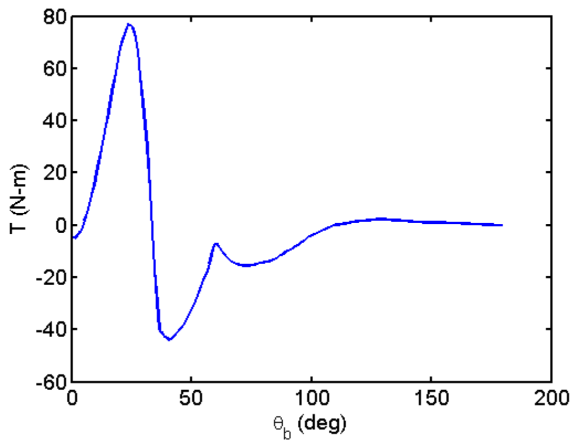

Figure 4: Torque vs. blade azimuth angle.

Guide Vanes

As was mentioned previously, guide vanes can also be used to address the problem of self-starting. Since the torque on a single blade is actually negative for a significant portion of each revolution (Figure 4), it would be beneficial to create positive torque through the intelligent placement of guide vanes. Indeed, not only does a positive torque mean the turbine will accelerate faster in the desired direction, but according to Islam, Ting, and Fartaj [2], if the net torque is also made to be positive for all tip speed ratios up to the operating speed, then this should be sufficient for self-starting.

The tangential coefficient is calculated in Eq. (5). In Figure 5, this value is plotted for a NACA 0015 airfoil at various angles of attack; here it can be seen that the tangential coefficient is maximized when the angle of

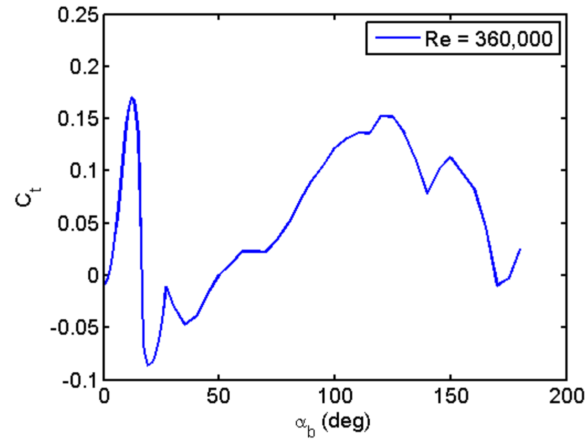

Figure 5: Tangential coefficient vs. blade angle of attack for a NACA 0015 airfoil.

attack is approximately 12°. Theoretically, the guide vanes can also be used to give the airfoils an angle of attack between approximately 100° and 160°—here the tangential coefficient is somewhat lower, but it stays relatively high for a wider range of values. However, the blades typically do not approach this range by themselves.

$$C_t = c_l \sin \alpha_b - c_d \cos \alpha_b \tag{5}$$

Guide vanes will need to be placed to the sides of the turbine and at azimuth angles where their necessary angle of attack is minimized in order to reduce drag losses. Looking at Figure 4, the greatest benefit will be realized for guide vanes at azimuth angles between 33° and 180°, since torque is either negative or very small in this range.

Drag Tubes

Drag tubes (which operate on the same principle as Savonius rotors) are another potential method of improving VAWTs' self-starting capability and are most effective at low tip speed ratios. Since Savonius rotors are always self-starting if there are at least two scoops at different angles, it is tempting to think of drag tubes as the perfect solution for the self-starting problem. However, according to Kirke [4], a drag tube rotor is only adequate for this job if:

- Its radius is "compatible with that of the Darrieus, so that it not only starts the rotor but continues to provide torque until the Darrieus can take over, and does not then produce negative torque which would reduce the overall efficiency of the turbine in its optimum operating range."

- It is "big enough to produce 'enough' starting torque."

It is apparent that in order to determine whether an auxiliary Savonius rotor is appropriate for a particular VAWT, the effects of the drag tubes must be examined in detail. The simulation assumes that the drag tubes are relatively long with a semicircular cross section, although other shapes can be used.

Whereas the lift and drag coefficients of different airfoils are generally well-documented, it is difficult to find this data tabulated against angle of attack for other geometries. It is known from Hoerner [1] that the drag coefficient of the semicircular tube is 2.30 when it is facing the wind and 1.20 when it is turned away, but this same information is not readily available for other angles of attack. Since it is mainly the drag of the tubes that produces torque, lift effects were neglected. (In any case, there was no lift data to be found, presumably because it is rare to generate lift using shapes other than airfoils.)

Curve fitting was utilized to generate drag data for one full rotation. The curve was assumed to be a sine wave of the form in Eq. (6) since the drag coefficient is minimized when α_b is 0° and maximized when α_b is 180°; A and D are constants.

$$c_d = A \sin \alpha_b + D \tag{6}$$

4 MOTOR-GENERATOR DRIVE

If the turbine is being used for electricity generation, a motor-generator may be attached for the purpose of spinning it up to operating speed. A motor-generator with high current, high voltage, and low "cut in" rpm is desirable since the turbine should produce a useful amount of power despite operating at a relatively low rpm. The battery used should be of the deep cycle variety, deep cycle batteries being better suited than car batteries for repetitive charging and discharging. Since intense fluctuations in voltage due to variations in wind speed can damage the battery, a charge controller is also necessary to regulate the voltage used to charge the battery. On the other hand, the current should bypass the charge controller when the battery is driving the turbine, as the battery should output a constant voltage.

Since it is assumed the VAWT is too large and heavy to start using wind alone, it can be started by initiating a charge or "kick" from a PIC for several seconds which will run through a MOSFET and into an electrical relay. There, the coil in the relay will guide the charge through the "not closed" and "common" terminals to the battery and motor. This will charge the battery and supply the motor with initial energy to power the turbine. Then, the charge will go all the way around through the battery, through a regulator, and around the PIC back through a diode before reaching the relay once again. Here, the relay will read it in the "not open" and "common" terminal which will then charge the battery and disengage from the motor so that the wind turbine will now be powering the battery. It is important to note that the relay and the motor have to match in terms of maximum voltage and current, and the charge controller has to be hooked up properly. Figure 6 shows this arrangement more clearly.

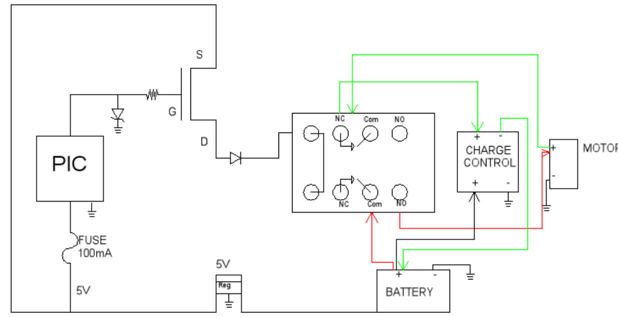

Figure 6: Circuit diagram.

5 BICYCLE DRIVE

Since one of the main goals of Georgia Tech's turbine is to be used in developing nations, a bicycle drive could provide a cheaper, human-powered solution to self-starting if the mechanism is kept as simple as possible. In conjunction with the simulation and other research on human factors, the goal is to determine how a human can, without excessive exertion, drive the turbine up to speed by pedaling on a bike held in place. Bicycle parts provide the advantage of being relatively cheap and easy to obtain, but challenges to be overcome include transferring power between two different axes (that of the bicycle's wheels and that of the VAWT), optimum gear ratios, whether or not gear shifting will be necessary (and if so, how to accomplish this), and how to disengage the bike from the turbine once it has spun up to speed.

Using only the gears already present on the bicycle frame, it is proven that the operator should be able to switch gears as needed to pedal the turbine up to the required tip speed ratio. From the gear relations given in Eq. (7) and Eq. (8), one can find the rpm that can be achieved at the rear tire where the assembly will be attached. Here θ is the angular deflection of the gear, r is the radius, N is the number of teeth, and T is the torque.

$$\frac{\theta_2}{\theta_1} = \frac{r_1}{r_2} = \frac{N_1}{N_2} \tag{7}$$

$$\frac{T_2}{T_1} = \frac{\theta_1}{\theta_2} = \frac{N_2}{N_1} \tag{8}$$

Assuming a gear ratio $\frac{N_{rear}}{N_{front}}$ of $\frac{14}{52}$ and an average cycling cadence of 60 rpm, the maximum achievable rpm at the rear will be 222.86 rpm. On the other end of the spectrum, a gear ratio of $\frac{28}{39}$ results in a rear angular velocity of 83.57 rpm.

6 CONCLUSION

It has been demonstrated that computer modeling can be a powerful tool for VAWT design, as it is cheaper than building multiple iterations of a turbine and makes it easier to visualize trends. The current state of simulation also shows the need for reliable airfoil data at low Reynolds numbers. A vertical axis wind turbine which is to operate for low tip speed ratios should have a relatively high solidity, but it should not be so high as to compromise its efficiency. It may also benefit from drag tubes and guide vanes, which can serve to increase the net torque or the torque of a single blade when it is in a dead band.

Finally, electrical or mechanical power provides an easy method of ensuring the turbine can start (though at the cost of autonomy). Either the circuit must sense when the turbine is not spinning at its operating speed, or someone must watch the turbine to see if it needs to be pedalled up to speed. Even so, both drive systems are capable of adding the necessary energy for a small-scale VAWT.

ACKNOWLEDGMENTS

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