Research and Development Summary for Small Wind Turbine Technology

Alex Butkus

12/20/14

1 - Introduction

The low Reynolds number wind turbine has applications in both on-grid and off-grid scenarios, with off-grid operations being the primary driving economic factor. The state of this technology, however, lags far behind commercial scale wind energy systems and poses significant hurtles that must be overcome for advancement to be achieved. These issues encompass engineering, economic, and political factors with emphasis placed on technical considerations in this document. While commercial exploration of wind turbine technology has taken priority for most governments the benefits of improving small wind energy systems are of great importance to those who do not have access to an electrical grid. Places, for example, where electricity will provide an opportunity to obtain fresh water or other "luxuries" common in first world nations. At the very least improving small wind energy systems will reduce energy costs and dependence on an electrical grid in case of power outages. This R&D summary will discuss the following aspects, beginning with the definition of a small wind energy system, following with a discussion of the state of the market and applications, a brief synopsis of aerodynamic issues at low Reynolds numbers and closing with proposed research avenues.

2 - Definition of a Small Wind Turbine

The definition of a small wind turbine is ambiguous by industry standards. Standards utilizing rated power or energy output are not necessarily clear because the technology has advanced considerably in the last 30 years. For example, Reference [1] noted that until the 1980s most large "commercial" wind energy systems were rated less than 100kW. The 2013 Global Wind Energy Report[2] noted a dramatic average rated power increase in offshore wind turbines starting at 450kW 23 years ago to 7-8 MW in 2013. Today, commercial producers such as GE advertise a power output of their newest turbines to be on the order of 1- 3 megawatts with their largest direct competitor Vestas advertising similar power specifications. Officially, according to a purchasing guide published by the Canadian Wind Energy Association[3] small wind energy can be classified by application: micro/recreational (less than 1 kW), battery charging (less than 5 kW), residential on-grid systems (1-10kW), and institutional on-grid systems (10kW-300kW). A similar consumer guideline published by the US Department of Energy[4] does not directly specify power output, but instead notes rotor diameters around 7.5 meters or less are considered small. This closely correlates with the Canadian publication definition of 10kW or less based on the figures they provided. Definitions utilizing blade diameter or blade area may initially appear to be a more absolute metric for wind turbine classification, but still suffer from the power-rating classification weakness in that these sizes are subjective and will change as the average size of wind turbines increase. A final interesting perspective on area-based classification was pointed out in Reference [1] through operational costs. Simply, an investigation conducted in Germany determined the following:

- Wind Turbines less than 40m^2 cost (on average) 16 Eurocents/kWh
- Wind Turbines from 40-200m^2 cost (on average) 3.5 Eurocents/kWh

This is not a trivial definition as it points out a glaring weakness in the feasibility of the small wind market: small wind turbines are more expensive than their commercial counterparts.

Formally, this paper defines a small wind turbine as a turbine which has an operating Reynolds number less than $5*10^5$, within the laminar and transitional flow regime as the focus of this research proposal is the aerodynamics and design of wind turbines operating in this regime. The graph below illustrates that this definition is consistent with the area-based and rated power-based definitions. The following graph was generated for a specific case, assuming a power coefficient 50% of the Betz limit, a tip-speed ratio of 5 and a blade aspect ratio of 8:

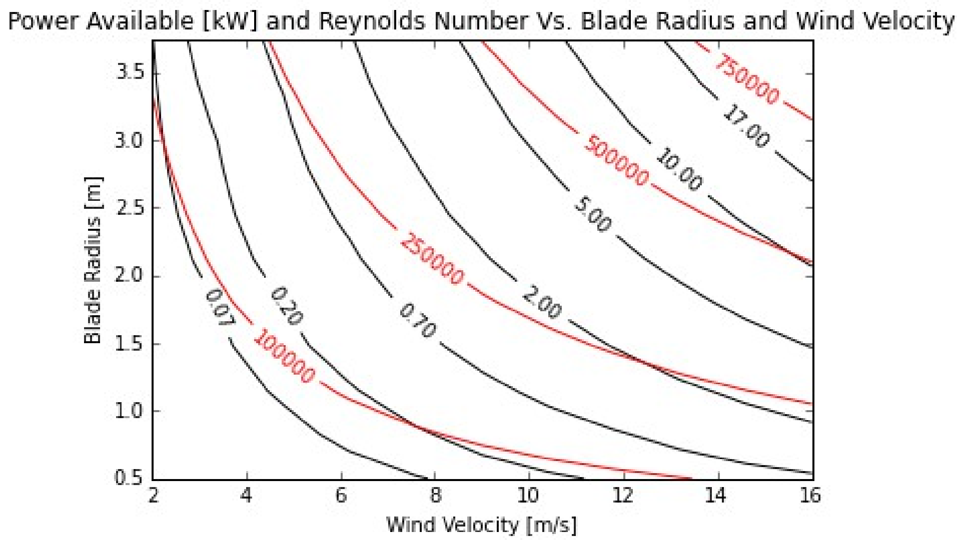

Figure 1: Power available (black) and Reynolds Number (red) contours as a function of blade radius and wind velocity. Using the definition based on Reynolds number, wind turbines with a capacity about less than 10kW are considered "small".

3 - The Current Market and Potential Applications

The market for small wind energy systems is increasing rapidly with many opportunities for expansion. Because most government policies have favored the development of commercial systems, the technology in this area is underdeveloped. The biggest market for small off-grid wind turbines is in remote power generation where isolated locations do not have access to on-grid electricity. Many authors[1, 5, 6,7,8] and others concede small wind energy systems would best serve 3rd world countries for applications such as water purification, communication, refrigeration, operating essential infrastructure (hospitals, schools, etc), and other luxuries developed nations enjoy with regular access to electricity. Additional applications may include battery recharging stations and augmentation with solar energy to provide continuous power.

The latter especially important for water purification processes where power available from wind energy will probably be intermittent. Reference [5] cited a specific study conducted by the NWTC and found that a combined electrodialysis reversal unit (see "Electrodialysis (ED) and Electrodialysis Reversal (EDR)."[9] for a technical summary of EDR devices) and ultraviolet water purification unit consumed about 159 watts operating at 8.5 hours a day (for a total of 636 hours) with an average wind speed of 4 m/s used. The power produced by wind in this case is more than sufficient to power these simple filtration devices, but did not provide the consistency necessary to optimize performance. In this case utilizing a solar array during the day, then batteries charged by small wind turbines at night, might be a possible solution.

In developing nations remote small wind turbines have applications to rural areas where on-grid access might be costly, not achievable or unnecessary. China is the leading user of small wind technology for this application with an estimated 450,000 units installed, followed by the USA and UK with 144,000 and 21,610 respectively according to the 2012 Small Wind Report[10]. The 2014 Update to the Small Wind Report[1] cited higher numbers overall, but no change in the general trend. On-grid uses in developed or developing nations may be feasible as well, where individual home owners may install small wind turbines to reduce their electricity bill and provide power back into the grid. In rare occasions remote power that would be utilized by 3rd world nations would be used in same way in first world nations. In these nations wider spread use of small wind energy systems has been plagued with problems stemming from a lack of established standards. Typically, this has lead to false advertising (lower than expected power output for example), potential safety hazards, misuse, low reliability, high cost per kilowatt, and concerns over noise production.

Finally, a very intriguing application of off-grid small wind turbines may come in the form of a power source for interplanetary settlements. Specifically, Mars is an extremely dusty environment[11,12] and consequentially may adversely affect the performance of solar energy systems. The density of air on mars is roughly 1% of that on Earth, however the thermal properties of the martian soil lead to large temperature gradients between night and day that result in very high wind speeds. A single masters thesis[13] (and perhaps one of a very small pool of related papers) identified this topic directly and designed a 500 watt wind turbine for this application.

4 - Technological Challenges

Political and economic factors aside, one of the biggest problems with small wind energy systems is the behavior of fluids at Reynolds numbers below 10^6. At higher Reynolds numbers where most aircraft, large UAVs, and commercial wind turbines operate, the flow is well understood and performance metrics are well documented. Paramount to the classification of flows between $10^4 < Re < 5*10^5$ is the presents of laminar separation bubbles that fundamentally change the behavior of conventionally design airfoils/wings[14]. As described in References [15] and [16], laminar separation leads to a rapid rise in drag, loss of lift, and drastic changes in moment coefficient. These issues are exacerbated at higher angles of attack leading to premature stall, and potential increased structural loading due to the abrupt change in moment coefficient. These separation bubbles can be categorized as “short/small” or “long/large” depending on the scenario. “Short” where there may be detachment of laminar flow close to the leading edge followed by reattachment further down the airfoil chord, en-training a small region of turbulent recirculating flow above the airfoils surface. “Long”, when the short bubble bursts, characterized as total separation spanning from the leading edge to trailing edge, bringing the airfoil to stalled conditions.

The flow regime characterized by $Re < 10^5$ further complicates wing and airfoil design. A very intriguing study conducted at Iowa State University[17] entailed a thorough investigation to capture the physics of the dragonfly wing operating at $Re=3.4*10^4$ and compared it to a conventional low Reynolds number wing section, the GA(W)-1. They discovered that the highly corrugated profile acted to both trip the boundary layer near the sharp peaks at the leading edge, while the troughs acted to trap vorticies delaying separation significantly. A similar follow up numerical study was conducted[18] comparing the dragonfly airfoil against the GA(W)-1 airfoil. Their study confirmed the results of Reference [17], but further noted that the initial 2D simulations performed were extremely poor predictors of performance, while the 3D results fared much better. The operating Reynolds number of these studies may lend themselves to micro-power applications and may be applicable to the Martian wind energy system described earlier.

Interestingly, extending the above characteristics to more conventional small wind turbine Reynolds numbers does not fare well for airfoil design. Selig showed[19, 20] that incorporating leading edge turbulators (whether to simulate roughness effects or as a deliberate strategy employed used at higher Reynolds numbers to delay stall) only served to degrade airfoil performance.
Roughness effects were especially pronounced, showing both reductions in Cl_{max} and the lift-to-drag ratio. Specifically, at a Reynolds number of $3*10^5$ an average drop in Cl of .19 was observed, with an average drop in l/d of 46.5 between the free transition and “forced” roughness simulated case. Selig noted, however, that the numbers his experiments yielded were “worst case scenario” based on his experimental set-up. This is an important point because the small wind turbine is expected to operate year round in a diverse set of weather conditions with minimal maintenance requirements. Freestream

turbulence, icing, soiling and other environmental factors are clearly not trivial concerns based on this data.

The literature cited in this section is a very small sample of work conducted on airfoils and wings operating in the low Reynolds number flow regime. Selig, Eppler and Drela, are well known their classes of airfoils and computer programs specifically designed for wings operating between $10^5<Re<5*10^5$. Their research is exhaustive and has provided the aerospace community with valuable tools and data necessary to design wing sections. The final section (below) discusses the proposed direction of research for this topic.

5 - Project Details

Extending on the concepts discussed above, an avenue of research that remains much less explored and has the potential for significant improvements in wind turbine performance may involve employing novel wing configurations with airfoils designed by those who have already explored wing section performance at low Reynolds numbers. Specifically, the employment of multiplanar configurations for wind turbine design might lead to substantial increases in power extraction and increased efficiency. At low wind speeds, this is especially important where the Reynolds number will be the lowest and is usually the deciding factor in requirements for economic feasibility. This section will discuss potential applications to darrieus-type VAWTs and HAWTs.

For the VAWT, a biplane-like arrangement of the wings may act to reduce drag and increase starting torque/lift at low speeds. Biplane wing aerodynamics were studied extensively by Munk about 100 years ago[21] and showed that there exists an optimum orientation between wings such that the induced drag can be minimized. Further, a favorable orientation of the biplane arrangement of the wings may reduce losses due to the trailing wake behind each blade, thus increasing efficiency. Darrius-type wind turbines are known to be non self starting, which today can be mitigated by augmenting a Savonious configuration to the design. While this usually leads to a self starting VAWT, the result is poorer performance during steady-state operations. The biplane wing may mitigate the need to augment a self-starting mechanism through enhanced lift per unit span (however lift coefficients will be lower due a larger reference area). In the context of a Micro Air Vehicle (MAV), it was shown in Reference [22] that significant increases in lift for low aspect ratio wings operating at a Reynolds number of about $1.5*10^5$. Another complete study by Munk[23] fully characterized biplane and triplane aerodynamics based on gap, stagger, and decalage. Unfortunately, it is not clear what (if any) corrections they made to their wind tunnel data, rendering only qualitative trends useful - the most interesting fact being that the Cl curves behaved quadratically with geometric angle of attack. The author did not come across any biplane literature that might pertain to propeller or VAWT design with one exception: a student driven report that was published in Proceedings of the 2013 Annual Conference of the American Society for Engineering Education. Unfortunately, most of today's literature of the subject is focused on biplane applications to MAVs, while most literature for conventional designs dates to around and before the 1920's

For the HAWT a unique “extruded axis” blade configuration may provide the benefits of increased solidity and blade number described in Reference [24], with the added advantage of reducing losses due to the trailing wake behind each airfoil. A 6 bladed configuration, for example, may employ 3 blades on a forward axis followed by an additional 3 blades some number (or fraction) of mean chord lengths behind the front rotor plane. For 12 blades, one might observe 3 rotor planes with 4 blades each extruded a total of a multiple of the mean chord length of the leading rotor. The objective in this case would be to investigate if a favorable aerodynamic interaction can be achieved between each set of wings, as can be done with biplane aircraft. The most similar design to this concept is a class of wind energy systems called Counter Rotating Wind Turbines (CRWT). The benefits of this design are well documented in Reference [25] and noted that the literature has cited power increases upwards of 20%, with their study demonstrating a maximum increase in Cp of 9.67% at 10 m/s with a separation of 65%

of the main rotor diameter between each set of blades. A numerical study conducted showed through integration of a fitted Weibull distribution representing wind speed at the Island of Sprogø (an uninhabited Danish island) showed 43% more annual energy (in kWh) could be produced compared with a counter rotating design compared with a conventional HAWT[26]. With that said, the Island of Sprogø may represent a uniquely excellent location for wind energy systems. A similar design was explored in Reference [27] which utilized a counter/co-rotating configuration depending on the wind speed with rotors in close proximity of each other. Unfortunately, in most cases claims such as these (in the sense that they promise extreme performance improvements) usually have a "catch". That is to say, if 20-40% energy extraction improvement can be achieved with a CRWT why haven't commercial manufactures utilized these designs?

The small wind turbine has an advantage from a research standpoint in that one can construct a working prototype with little resources compared to a commercial system, while simultaneously yielding data that needs less extrapolation to be applicable to a marketable system. It was discussed earlier that the small wind energy market has problems with "false advertising" - manufacturers often list their performance metrics as a numerical value computed from the swept blade area and wind velocity, with no attention to "real world" effects (low Reynolds number aerodynamics, generator design, etc). Reference [7] provides excellent documentation of the difficulties associated with small wind energy systems from aerodynamic, structural, electrical, and systems engineering standpoint. It is clear from this publication and many others listed in the references that the most reliable (and probably only viable) metric of performance for the small wind turbine is not wind tunnel testing or computer simulations, but the testing of a prototype over an extended period of time. While the emphasis of this R&D summary has been focused on aerodynamic considerations, the most important aspect of this research is that the work conducted culminates to a working prototype, tested over a period of at least a few months, that clearly and unambiguously demonstrates the superiority (or maybe inferiority!) of a multiplanar design over a conventional counter-part. Only though this level of investigation can a marketable prototype be developed from the research efforts of this proposal - the long term goal of this investigation.

6 - Closing Remarks

In conclusion, the objective of this project proposal is to explore multiplanar configurations applied to wind turbines. The specific examples cited in the previous sections serve to demonstrate potential benefits of exploring this technology and the importance developing a marketable prototype. Research into the small will turbine will accomplish three major things: improved performance, expand the market and potentially help people. The first and second points tie closely together – as it stands now the cost of a small wind turbine per kWh is greatly prohibitive compared to large scale commercial solutions. As it was explained, a good portion of this problem is due to the aerodynamics of wings at low Reynold numbers. The utilization of mutiplanar blade configurations may act to offset the detrimental aerodynamic effects by increasing the lift per unit span (resulting in increased torque and potentially a lower cut-in wind speed) and induced drag reduction. A lower cut-in wind speed will permit use of small wind energy systems in locations where the average wind speed was deemed too low for economic viability. If induced drag can be reduced, then there is also a potential for increased wind turbine efficiency.

The third point, helping people, is where the true benefit of this technology resides. Hypothetically, an improvement in energy output for a remote village in a 3rd world country may mean more access to clean water, refrigeration, communication or medical services previously unavailable. At the micro-scale, this may provide an individual (say, an ejected pilot) the ability to temporarily charge a portable radio or extend the life of their communication devices by several hours, providing them valuable time to contact help. And lastly, grid connected small wind energy systems may see beneficial reductions in costs of electricity or less dependence on an electrical grid. It is clear that more work needs to be conducted on small wind energy systems, but it is crucial that marketable prototypes are developed to clearly demonstrate potential benefits of the aforementioned designs.

7 - References

[1] "2014 Update Small Wind World Report." (2014). Print.

[2] "Global Wind Report, Annual Market Update 2013." (2013). Print.

[3] "Small Wind Turbine Purchasing Guide, Off-grid, Residential, Farm & Small Business Applications." Canadian Wind Energy Association. Print.

[4] "Small Wind Electric Systems, A US Consumers Guide." (2007). Print.

[5] Corbus, D., I. Baring-Gould, S. Drouilhet, V. Gervorgian, T. Jimenez, C. Newcomb, and L. Flowers. "Small Wind Turbine Testing and Applications Development." (1999). Print.

[6] McGowan, Ryan, and Narayanan Komerath. "Vertical Axis Micro Wind Turbine Design for Low Tip Speed Ratios." Print.

[7] Probst, Oliver, Jaime Martinez, Jorge Elizondo, and Oswaldo Monroy. "Small Wind Turbine Technology." Www.intechopen.com. Print.

[8] Ruin, Sven, and Sven-Erik Thor. "Challenges of Introducing Reliable Small Wind Turbines." *Summary of IEA RD&D Wind – 49th Topical Expert Meeting* (2006). Print.

[9] "Electrodialysis (ED) and Electrodialysis Reversal (EDR)." (2010). Us Department of the Interior Bureau of Reclamation. Web. <http://www.usbr.gov/pmts/water/publications/reportpdfs/Primer Files/07 - Electrodialysis.pdf>.

[10] "2012 Small Wind World Report." (2012). Print.

[11] Cantor, B.A. "Present Day Martian Weather– 5 Mars Years of Observation By MGS-MOC and MRO-MARCI." *Seventh International Conference of Mars*. Print.

[12] Spiga, Aymeric, and Stephen Lewis. "Martian Mesoscale and Microscale Wind Variability of Relevance for Dust Lifting." *The Mars Journal* (2010): 146-58. Print.

[13] Kumar, Vimal, Marius Paraschivoiu, and Ion Paraschivoiu. "Low Reynolds Number Vertical Axis Wind Turbine for Mars." *Wind Engineering* (2010): 461-76. Print.

[14] Alam, Md. Mahbub, Y. Zhou, H. X. Yang, H. Guo, and J. Mi. "The Ultra-low Reynolds Number Airfoil Wake." *Experiments in Fluids*: 81-103. Print.

[15] Karasu, Ilyas, M. Serdar Genc, and H. Hakan Acikel. "Numerical Study on Low Reynolds Number Flows Over an Airfoil." *Journal of Applied Mechanical Engineering* 2.5 (2013). Print.

[16] Crivellini, A., V. D'Alessandro, D Di Benedetto, S. Montelpare, and R. Ricci. "Study of Laminar Separation Bubble on Low Reynolds Number Operating Airfoils: RANS Modelling by Means of an High-Accuracy Solver and Experimental Verification." *Journal of Physics* (2014). Print.

[17] Tamai, Masatoshi, Zhijian Wang, Ganesh Rajagopalan, Hui Hu, and Guowei He. "Aerodynamic Performance of a Corrugated Dragonfly Airfoil Compared with Smooth Airfoils at Low Reynolds Numbers." Print.

[18] Gao, H., Hui Hu, and Z.J. Wang. "Computational Study of Unsteady Flows Around Dragonfly and Smooth Airfoils at Low Reynolds Numbers." (2008). Print.

[19] Selig, Michael S., and James J. Guglielmo. "High-Lift Low Reynolds Number Airfoil Design." *Journal of Aircraft*: 72-79. Print.

[20] Giguère, P., and M. S. Selig. "New Airfoils for Small Horizontal Axis Wind Turbines." *Journal of Solar Energy Engineering*: 108. Print.

[21] Munk, Max M.. General Biplane Theory. Print.

[22] Maqsood, Adnan, and Tiauw Hiong Go. "Parametric Studies and Performance Analysis of a Biplane Micro Air Vehicle." *International Journal of Aeronautical and Space Sciences* (2013): 229-36. Print.

[23] Munk, Max M.. "The Air Forces On A Systematic Series Of Biplane and Triplane Cellules"

[24] Duquette, Matthew, and Kenneth Visser. "Numerical Implications of Solidity and Blade Number on Rotor Performance of Horizontal-Axis Wind Turbines." *Journal of Solar Energy Engineering* 125 (2003): 425-32. Print.

[25] Kumar, P Sanathana, A. Abraham, R. Joseph Bensingh, and S. Ilangovan. "Computational and Experimental Analysis on Counter Rotating Wind Turbine Systems." *Journal of Scientific and Industrial Research* 72 (2013): 300-06. Print.

[26] Shen, W Z, V A K Zakkam, J N Sørensen, and K. Appa. "Analysis of Counter-Rotating Wind Turbines." *Journal of Physics: Conference Series* (2007): 012003. Print.

[27] Usui, Yuta, Koichi Kubo, and Toshiaki Kanemoto. "Intelligent Wind Power Unit with Tandem Wind Rotors and Armatures (Optimization of Front Blade Profile)." *Journal of Energy and Power Engineering* (2012): 1791-799. Print.

8 - Further Reading

[a] Hobbs, William B., and David L. Hu. "Tree-inspired Piezoelectric Energy Harvesting." *Journal of Fluids and Structures* (2011): 103-14. Print.

[b] J. Lassig and J Colman (2012). Wind Turbine Aerodynamics, Applied Aerodynamics, Dr. Jorge Colman Lerner (Ed.), ISBN: 978-953-51-0611-1, InTech, Available from: http://www.intechopen.com/books/applied-aerodynamics/wind-turbines-aerodynamics

[c] Kunz, Peter, and Ilan Kroo. "Analysis, Design, and Testing of Airfoils for Ultra-Low Reynolds Numbers." Print.

[d] Letcher, T. "Small Scale Wind Turbines Optimized for Low Wind Speeds." Print.
Li, Shuguang, and Hod Lipson. "Vertical-Stalk Flapping-Leaf Generator For Wind Energy Harvesting." (2009). Print.

[e] Ragni, Daniele, Carlos Ferreira, and Matthew Barone. "Experimental and Numerical Investigation of an Optimized Airfoil for Vertical Axis Wind Turbines." AIAA 2014-0171 (2014). Print.

[f] "Third quarter 2014." *Vestas*. Web. 8 Dec. 2014. <http://www.vestas.com/>.

[g] "Wind Turbines - Wind Power | GE Energy." *GE Energy*. Web. 8 Dec. 2014. <http://www.ge-energy.com/wind>.