Evaluation of Centimeter-Scale Micro Wind Mills:
Aerodynamics and Electromagnetic Power Generation

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ABSTRACT

We have experimentally investigated the performance of miniature wind mills for micro power generation, including centimeter scale wind turbines, sub-watt electromagnetic generators, and their integration. This paper covers wind energy harvesting fundamentals, followed by the effect of miniaturization on wind turbine aerodynamics and their efficiency, the experimental characterization of small commercial electromagnetic generators, and the demonstration of power generation up in the 1-100 mW range. An efficiency of 1.5 % has been achieved with 5.5 m/s wind speed, using a 4.2 cm diameter turbine and 9.5 % efficiency at 11.8 m/s.

1 – INTRODUCTION

In the last few years, miniature wireless sensors have become increasingly popular to monitor our environment, such as temperature, pressure, airspeed or toxicity of air. Such sensor nodes could be implemented everywhere, from the top of a mountain to ventilation ducts in buildings. These devices need a very small amount of energy, on the order of a few milliwatts, to transmit the data to a wireless base station. This electrical power can come from a limited source, like a battery, or by harvesting energy from the environment. Different sources of energy have been studied recently for energy harvesting [1], such as vibration, heat, or solar power, but very limited work has been done on wind power at small scale [2].

At large scale, windmills are well documented and can operate near the maximum theoretical power. This is not the case for miniature windmills, which operate at a much higher speed and low Reynolds number. Power generation is also affected by the generator, especially if it is not designed for this application. This paper describes the most recent research in the characterization of small windmills. Following a description of the typical environment, the experimental set-up, aerodynamic performance of the propeller and electromagnetic power generation will be detailed.

2 – WIND POWER PLANTS

The available wind power can be defined as: $\dot{W}_{wind} = \frac{1}{2}\rho V^3 S$, where V is the incoming wind velocity and S the area swept by the wind turbine [3]. Based on the classical wind mill theory of Schmitz [3], the maximum turbine efficiency increases with the tip speed ratio, $\lambda = \omega R / V$, up to a maximum theoretical value of 59%. In practice, large wind turbines can achieve over 50% efficiency at $\lambda > 6$. The turbine efficiency is defined as the power extracted from the wind (torque $\times$ speed) over the kinetic energy available for the area covered by the disk of the propeller.

By increasing λ, the angular speed is higher for the same airspeed and less energy is lost as downstream swirl. More power can therefore be extracted with a higher λ, but the torque is reduced. Then, it is necessary for these devices to have a variable pitch propeller or even use the generator as a motor to start the windmill. Changing the pitch of a propeller is usually reserved to large power plants due to its complexity and cost. Gearboxes are also used in large windmills to match the generator requirements. In tiny applications, a gearbox can reduce the efficiency by 50% [4] and would also be expensive. For small scale wind power plants, it seems preferable to match the turbine rotation speed to that of the generator to allow a direct drive. For a fixed pitch propeller, the best operating condition is called λ_d which is function of the geometry. If the propeller is used in a different condition, $\lambda \neq \lambda_d$, so the efficiency will be lower.

The turbine aerodynamics at small scale will be affected by lower operating Reynolds numbers ($Re < 10^5$). In this range, a lift-to-drag ratio of around $\varepsilon \sim 10$ is expected for a thin cambered airfoil, based on 2D CFD calculation and the literature [5,6]. Figure 1 presents the maximum efficiency as a function of the number of blades, n, design tip speed ratio, λ_d, and lift-drag ratio, ε, of the airfoil. For an airfoil with a lift-drag ratio of around 10, the highest theoretical efficiency (with the perfect blade geometry) varies from 25 to 40 %, depending of the number of blades, for $1.5 < \lambda_d < 3.5$.
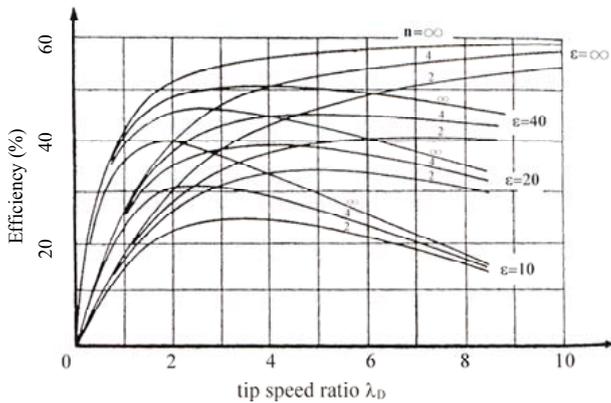
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Figure 1 - Maximum efficiency of a wind turbine from the Schmitz theory [3]

The effects of the 2-D aerodynamic performances of the airfoil become more important with increasing λ_d. The less efficient the airfoil is, the lower the optimum λ_d will be. The maximum efficiency and the design tip speed (i.e. power density) are therefore expected to be lower for micro windmills.

3 – TYPICAL ENVIRONMENT

The average wind speed in Canada is around 5 m/s, depending on the area, the season and the time of the day [7]. Close to the ground however, important effects of viscosity appear, reducing the velocity. For internal flow, such as ventilation ducts, the air velocity can reach 12 m/s in large ducts, down to 1-2 m/s close to the exit in rooms. The air duct application has significant advantages for tiny windmills; the constancy of the wind, combined with the absence of rain, snow and ice provide a well controlled environment. Also, the airspeed can be higher, providing a lot more energy.

4 – EXPERIMENTAL SETUP

A set of experiments has been done to study the difference between the efficiency of large windmills compared to a centimetre scale one. Another goal was to study the integration with an electromagnetic generator to evaluate the complete assembly efficiency and optimisation.

The wind tunnel used has a 35 cm diameter test section with a settling chamber at the entrance. Airspeed is measured using a Pitot tube with a differential pressure transmitter, providing reading with an accuracy of ±0.5 % of the flow velocity. Full control on the airspeed was possible, which allowed tests from 0 to 23 m/s. All tests were done at an ambient temperature of 20°C. A complete characterisation of the wind tunnel showed no large boundary layer close to the wall, even at 2m/s (at more than 3 cm of the wall). All the tests were done in the center of the test zone, with the Pitot tube at 10 cm offset to be away from the axis of rotation of the windmill, 5 cm forward of the turbine.

The torque created by the propeller of the windmill is measured using small commercial electric motors, like pager motors or small R/C airplane motors. In this experiment, we used the low-cost brushed DC motor model "Speed 265" from Graupner [8] for its repeatability during characterization. Previous to the experiment, a complete characterization was done to know the internal friction and torque constant as a function of the speed. The torque constant, K, was found by driving the motor with another motor. The voltage generated in open circuit divided by the speed of rotation gives the torque constant, $K=V/\omega$, with an uncertainty of 0.1 %. The speed was determined by measuring the period between each pulse created by the generator with an oscilloscope (Agilent, DSO6014A, 100 Mhz), and validated by an optical displacement probe (Philtec Inc.).

The friction torque ($C_{Friction}$) curve was obtained with a no load test, at a known current and speed using this equation: $C_{Friction} = C_0 + \omega K_{Friction}$, where C_0 is the constant friction and $\omega K_{Friction}$ the viscous friction. A curve fit of the friction as a function of speed was obtained: $C_{Friction} = 9.64\text{x}10^{-5} \omega + 0.145$ [N·mm], with $R^2 = 0.996$, with ω in rad/s.

The complete windmill was installed in the wind tunnel, in the middle of the test zone. The torque is controlled on the generator by changing the electrical resistance between the generator connectors, using a 100 ohms and a 500 ohms potentiometer. The current is measured by an ammeter (Extech Instruments) and the voltage is measured directly on the oscilloscope. Electrical power is calculated directly as the product of current and voltage. Mechanical power delivered by the propeller to the generator is given by the friction curves and torque constant K from this equation: $P = T\omega = (Ki + C_{Friction})\omega$. The propeller efficiency can be defined as the ratio of the mechanical power over the kinetic energy of the wind crossing the area swept by the wind turbine. The overall efficiency is defined as the ratio of the wind power over the electrical power generated.

Using this setup, a 4.2 cm diameter propeller with 4 blades was tested with different pitch angles, shown in Figure 2. The propeller was taken from an S.C. Johnson consumer product.
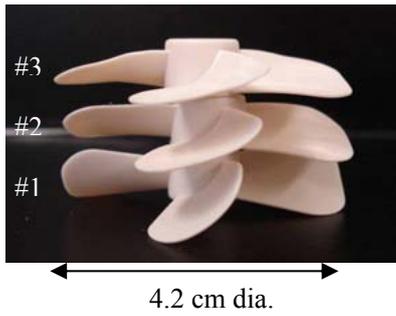
Figure 2 – The three propellers tested
#1 : 46°stagger, #2 : 26° at the tip, #3, 19° at the tip.

The reference propeller (#1) has been tested from 5.5 m/s to 11.8 m/s with a total of 5 different airspeeds. The two others were tested at 10.25 m/s. For each run, the load on the generator was changed from open circuit to closed circuit using the potentiometers, which changed the speed of rotation. These propellers were not modified to fit the Schmitz theory in term of blade angle (to fit with a particular λ). This factor reduces the achievable efficiency.

5 – RESULTS AND ANALYSIS

5.1 - Turbine efficiency

The first parameter studied is the relation between the efficiency and λ, for different airspeeds using turbine #1, with a λ_d of 0.8. Within an accuracy of 10 %, the efficiency of a turbine is not function of the strength of the wind, but only a function of the dimensionless parameter λ, for a constant geometry. Within this 10% difference, no relation can be established between the airspeed and the efficiency since the Reynolds number didn't change sufficiently to affect the turbine efficiency. The efficiency of the turbine versus λ is presented in Figure 3.
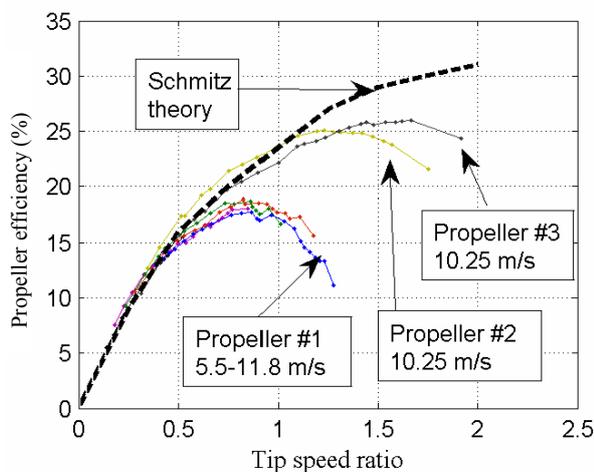

Figure 3 - Efficiency of the turbine versus the tip speed ratio, $\lambda=\omega R/V$.

This same experience, using propeller #2 and #3, showed the importance of the pitch on the efficiency, as the pitch of turbine #3 is less than half the pitch of #1. As stated in the Schmitz theory shown in Fig. 1, the maximum efficiency expected for a specific geometry increases with the augmentation of λ_d, up to a point where the blade drag overcomes the benefit of speed, and the maximum efficiency drops. The experimental data follows the theory with the increase in maximum efficiency for turbines #2 and #3, although our range of tests has not shown the reduction in efficiency that would occur at very low pitch angles. The maximum efficiency at λ_d obtained experimentally for each propeller is close to the Schmitz theory, which means that this theory, developed for "regular size" wind turbine, is also valid for small size devices.

5.2 - Power generation

Using propeller #1, with airflow between 5.5 and 11.8 m/s, we calculated the electrical power generated. The results are presented in Figure 4.

As expected, the maximum power increased with an augmentation of the kinetic energy of the wind. A maximum of 130 mW has been achieved with 11.83 m/s wind speed, which is not common in normal environments. With 5.5 m/s, the maximum power achieved is 2.4 mW, which is much smaller than 16.7 mW expected with the same efficiency of the whole windmill. Figure 5 shows the evolution of the overall efficiency of the windmill for different airspeeds.

The maximum overall efficiency was 9.5 % at 11.83 m/s but the maximum efficiency at 5.5 m/s was as low as 1.85 %.
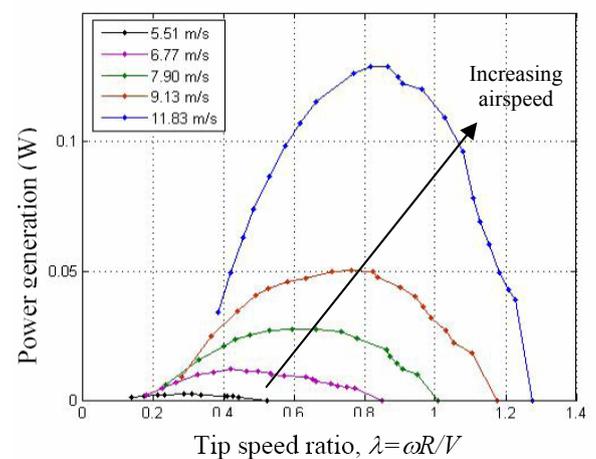

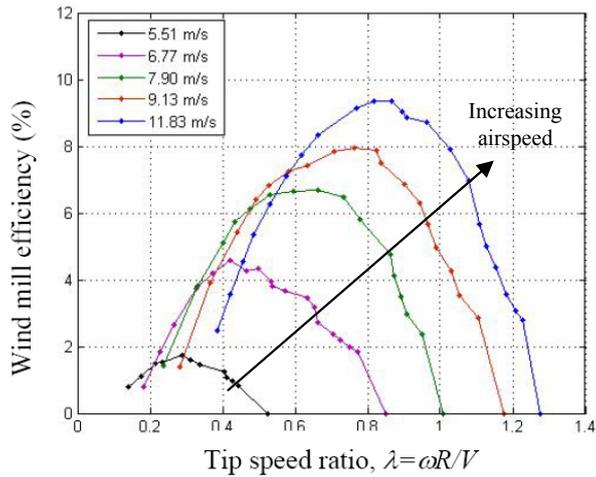**Figure 4 –** Power generated versus the tip ratio

Figure 5 – Wind mill efficiency versus the tip ratio

Figure 6 – Generator efficiency versus tip speed ratio

So, while the efficiency of the turbine stays constant with wind speed, the efficiency of the generator changes a lot depending on the power generated. A plot of the efficiency of the generator versus λ is shown in Figure 6. The speed of the generator is proportional to the tip speed ratio, for the same airspeed.

The maximum efficiency for the generator varies from 53 % down to 19 % for winds of 11.8 to 5.5 m/s respectively. This large variation in efficiency is caused by friction in the generator, internal electric resistance and the power extracted. No current means zero efficiency as all the mechanical energy goes in friction. On the other end, a high current reduces the voltage across the generator connectors, which reduces the efficiency as a lot of power is dissipated as heat in the coils.

Other than the electrical power, voltage is another important aspect. Considering turbine #1 at $\lambda=0.409$ and 5.51 m/s, even if the power can be sufficient for some wireless application, the voltage is very low, at 0.60 V compared to 2.6 V at 11.83 m/s, both at maximum efficiency . This is on the lower limit acceptable for solid state DC-DC converters [9].

6 – CONCLUSION

We think that low cost micro windmill can be a viable solution, depending on the required power, the minimum voltage and the diameter of the turbine acceptable. The larger the turbine, the more kinetic energy it can harvest.

Our experiment showed that the efficiency of the wind turbine follows the Schmitz theory, even at small size (4.2 cm diameter). The best efficiency achieved was 9.5 % in 11.83 m/s wind.
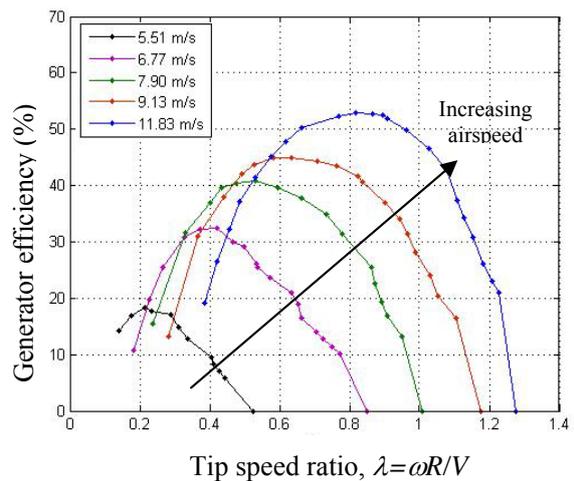
At low power and low wind speed, friction in the generator and electric resistance reduced the energy conversion so the maximum efficiency was only 1.85 % and the power provided was 2.4 mW, at 5.5 m/s air speed. Long lasting wireless sensors to monitor air quality in ventilation ducts could be well served by this technology.

7- REFERENCES

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