Design and optimization of Small Scale Wind Turbines for Low and high Speeds

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ABSTRACT

Wind-tunnels represent a useful tool for investigating various flow phenomena. An advantage of using wind-tunnels is that experiments there can be performed under well controlled flow circumstances compared to experiments in the open environment. The drawback is that small scale models often have to be used instead full scale ditto. To achieve the same Reynolds number as for the real application, the kinematic viscosity or flow velocity normally has to be changed. In most wind-tunnels air at atmospheric pressure is used, and the only option left is to increase the flow velocity. Often it is not possible to increase the velocity enough, so the results from wind-tunnel experiments fall in between those achievable.

Keywords- low wind speed, wind tunnel

I.INTRODUCTION

There are many types of wind-tunnels and they can be classified by e.g. flow speed dividing them into four groups.

1.subsonic or low-speed wind-tunnels

2.transonic wind-tunnels

3.supersonic wind-tunnels

4.hypersonic wind-tunnels

Subsonic or low-speed wind-tunnels are the most common type and the wind- tunnel described in this paper is of this type. Transonic wind-tunnels are common in the aircraft industry since most commercial aircraft operate in this regime. Supersonic wind-tunnels can be used to investigate the behavior of jet engines and military aircraft. Hypersonic wind-tunnels find their applications in rockets and space vehicles. A further way to categorize low-speed tunnels is by dividing them into open circuit or closed circuit wind-tunnels. In open circuit wind-tunnels there is no use for corners and long diffusers but the power needed to drive the wind-tunnel is high because of the loss of energy in the out- flowing air. Closed circuit wind-tunnels recirculate the air and thus normally need less power to achieve a given flow speed, see section 2, and, above all, facilitate the achievement of well controlled flow conditions in the test section. The present, and most low-speed tunnels used for research, are of the closed circuit type. Wind-tunnel design is a complex field involving many fluid mechanics and engineering aspects and it is impossible to cover them all in just one paper. Some books and articles have been written about this topic and e.g. Rae & Pope (1984), Bradshaw & Pankhurst (1964) are useful references when de-signing and constructing low-speed wind-tunnels. See also the comprehensive report on the German-Dutch Wind-tunnel edited by Seidel (1982). The first wind-tunnel at the Royal Institute of Technology was completed in the summer of 1932 at a newly constructed laboratory for aeronautical sciences. It had a closed circuit and an open jet test section, i.e. the test section had no walls. The test section was cylindrical in shape with a diameter of about 1.6 m and a similar length. It was primarily used for measuring forces on aircraft models and airfoils. It had an axial fan and corners with simple guide-vanes made of bent plates in the shape of 1 -circles. The contraction ratio was about 45 and the maximum speed in the test section about 50 m/s, see Malmer (1933). It was later modified with, among other things e.g. a closed test section, and was in use until only a few years ago. A number of other wind-tunnels for aeronautical research have existed over the years at KTH. Another low-speed tunnel, (formerly known as L2 now Design and evaluation of a wind-tunnel with expanding corners 3 L2000), was built in 1963 and is still used for aeronautical research. It has a 3 m long test section of 2 Ã— 2 m2 cross section and a maximum speed of 62 m/s. A supersonic, a hypersonic and a ballistic wind-tunnel are also part of the early aeronautical research history at KTH. In 1990 the MTL low-turbulence low-speed tunnel was inaugurated. The present tunnel complements the MTL-tunnel in several respects, both in research projects and in teaching. In particular it fulfills the need of a test section with very flexible design to allow e.g. strong pressure gradients etc. The limited available space made it necessary to use innovative design ideas that could allow a large enough test section for research projects, such as high Reynolds number turbulent boundary layer studies, into a small size wind-tunnel. There are some possibilities to reduce the overall size of a closed circuit wind-tunnel without making the test section smaller. One obvious way is to decrease the contraction ratio, CR, i.e. the ratio between the largest cross section are, (found in the stagnation chamber), and smallest cross section area, (found in the test section). Most large wind-tunnels already have quite small contraction ratios though, CR â‰¤ 6. One should keep in mind that a high contraction ratio is a key factor in achieving a good flow quality. Another way to reduce size is to use wide-angle diffusers. The use of wide-angle diffusers is a fairly common method to reduce the overall circuit length. The resulting losses, though, are rather high and accompanied by increased level of flow

disturbances. Finally there is also the possibility to use expanding corners which is used in this wind-tunnel. Expanding corners have a larger outlet than inlet cross section area reducing the need for long diffusers, see section 2.3, and can thus reduce the total wind-tunnel circuit length by about 20% without a large increase in total pressure-loss. The idea of using expanding corners has been around for a long time, e.g. Friedman & Westphal (1952), Collar (1936), Wolf (1957) and Kr Ìˆber o (1932) made some interesting experiments on expanding bends. However, most of the early results were not too encouraging, so the idea was put aside until recently. One of the reasons for the unfavorable results were the use of simple guide-vane shapes. When there is a large expansion, (expansion ratio of e.g. 1.316), in such a short distance a lot of effort has to go into the design of the guide-vanes to avoid boundary layer separation and a large total pressure-loss. Today, some new or planned wind-tunnels use expanding corners both at universities and in the automobile industry. The concept of expanding corners is especially useful in large wind-tunnels, because of the reduction in the total wind-tunnel circuit length.

II.THE WIND-TUNNEL DESIGN

In 1995 it was decided to build a new low-speed wind-tunnel as a complement to the larger MTL wind-tunnel already operating at the Department of Me- chanics, KTH, Stockholm, see Johansson (1992) and Lindgren & Johansson (2002).Aside from reducing the user load on the larger MTL wind-tunnel by the purpose of the new tunnel was also to give the undergraduate students the possibility to work with a new state of the art wind-tunnel. A primary aim was to here accommodate experiments that require a large degree of flexibility of the test section geometry. To meet these requirements it was necessary to specify design criteria that are close to those of the MTL wind-tunnel thereby simplifying the transfer of projects between the two wind-tunnels. The main design criteria are listed in the table below,

1.Closed circuit wind-tunnel.

2.Good flow quality (mean flow variation, turbulence intensities & temperature variation).

3.Contraction ratio, CR, of 9.

4.Test section aspect ratio of 1.5 and the maximum test section length possible in the available space.

5.Maximum flow speed in the test section of at least 40 m/s.

6.Low noise level.

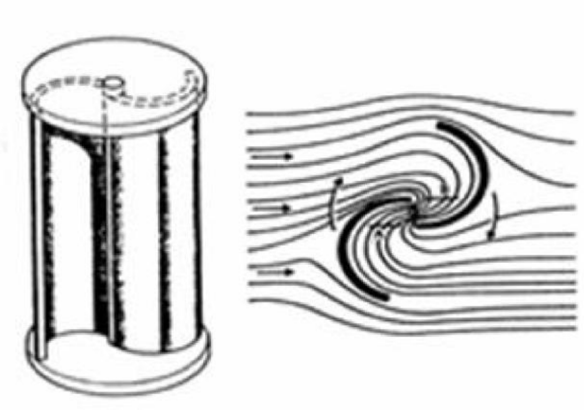
7.Low cost.

Design and evaluation of a wind-tunnel with expanding corners 0.45

III.DESIGN DECISIONS

The hybrid wind turbine design for this project was developed through research of current commercial design and a thorough literature survey. The team believed combining the Darrieus and Savonius type rotors on one axis would allow for self-starting as well as speed control by the drag-type Savonius. Many configurations were considered but not chosen for this project including single- or three-stage Savonius, twisted geometry Darrieus blade profiles and convergent nozzles. The original study by Savonius [1] only considered a single basic rotor design. The classic Savonius rotor does not have any airflow between "buckets" (see Figure 2). In the classical Savonius style, the buckets are connected or a pole is blocking the flow between the buckets.

Figure 1. Classic Savonius Rotor with no air flow between buckets.



Subsequent studies by researchers have shown that allowing air to flow between each side of the rotor dramatically improves the efficiency. A simple modification to the original study by Savonius by overlapping the rotors (see Figure 2), and thus allowing air to flow between each of the sides, significantly increased the efficiency. Fujisawa [2] experimented with different numbers of stages and experimentally measured the efficiency of each combination. This study concluded the two stage overlapping Savonius rotor was the most efficient of the combinations tested. This also allowed the turbine to be started with wind from any direction because offsetting the stages will ensure that one "bucket" is always in the direction of the wind. Twisted blade profiles have also been tested in the literature, but were not used in the current project because they would have been difficult for the team to fabricate with the given time allowed and the efficiency benefit was negligible.

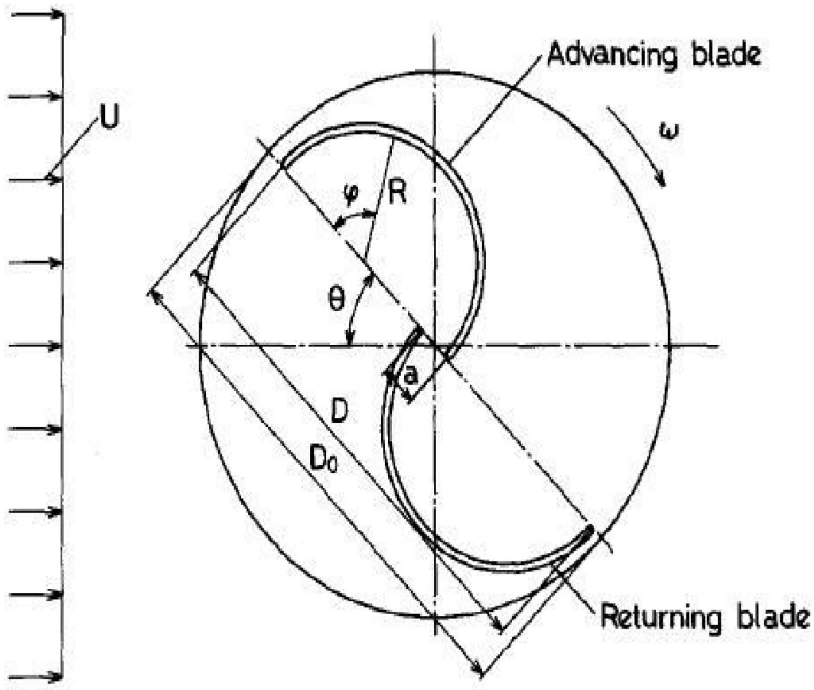


Figure 3. Overlapping Savonius rotors.

A slightly more efficient design (see Figure 4) was studied by Modi [3]. This design, although slightly more efficient, is much more complicated to manufacture and ensure perfect alignment. Ultimately, it was decided that the savings in manufacturing cost and reliability was more important than a small increase in efficiency.

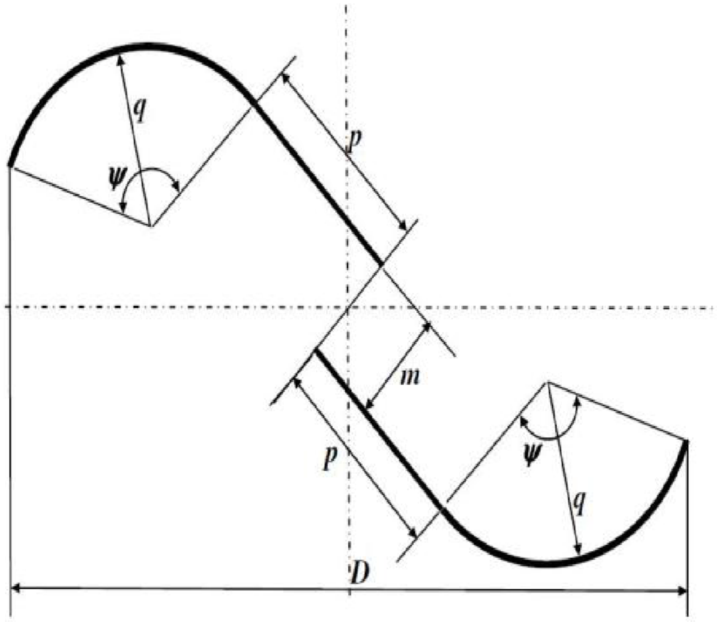


Figure 4. Modified Savonius rotor.

Another method to increase efficiency is to add converging [4]. Converging nozzles (see Figure 5) increase the velocity as it comes into the "torque" side of the rotor and also deflects air from the "anti-torque" side. Although this increases the air speed through the turbine, it changes the entire design of the turbine because the turbine now has to be rotated in the direction of the wind, eliminating the "accepting wind in any direction" aspect of the design.

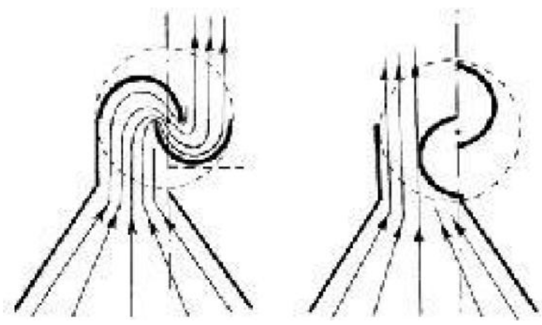


Figure 5. Converging nozzles on Savonius rotor.

The same type of design aspects and decisions had to be made for the design of the Darrieus portion of the design. In reviewing current commercial models of Darrieus rotor turbines, all turbines were optimized for high wind speeds. In addition, the standard design "rules" were also for high wind speeds. This information was taken into consideration when designing the Darrieus portion of our turbine design.

The most common Darrieus blade profiles are the NACA 0012 and NACA 0015 - which are both symmetrical profiles. Guillaume [5] studied the difference between the standard symmetrical profiles and specially designed cambered profiles. This report claimed the S2027 blade profile increased overall energy produced by about 16% over the standard NACA 0015. The group chose to test the two standard symmetrical blade profiles and the S2027 cambered profile to verify these claims.

The number of Darrieus blades was another design parameter. Current commercial Darrieus turbines use between three and nine blades. Some turbines do use a large number of blades, although typically only for large turbines. The group could not find any information on how to choose the number of blades so to reduce costs of manufacturing; the group chose three blades, which was the common number of blades for turbines of similar size.

Chord length was the last design parameter considered. The chord length makes the most impact on the torque produced. The standard design convention for Darrieus turbines is a chord length of about 10-20% of the length of the blade - but this design standard is meant for high wind sites. With lower wind speeds, less torque will be made by each blade. In order to compensate for some of this torque loss, the group tried increasing the chord length of each blade. This has consequences, such as increased cost to manufacture, increased weight and increased moment of inertia that hinders the turbines ability to increase speed quickly.

Several options were available for measuring the power the turbine produced with varying levels of cost and accuracy. The cheapest and least accurate method was to use a "rope break dynamometer" [9] (see Figure 6). The rope break can be successfully used in large applications, but the group was unsuccessful using this option when the torque being measured was so small. The next option was to use a cantilever beam attached to the resistance motor with a strain gauge mounted on the surface of the beam. In theory, the strain gauge measures the strain in the beam, which is only caused by the torque the wind turbine is producing. In practice, the strain gauge measured other unwanted effects, such as wind and vibrations.

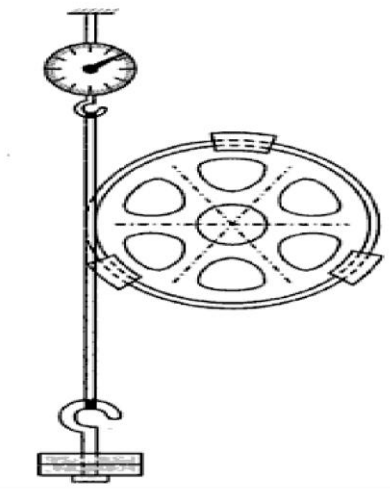


Figure 6. Rope break dynamometer.

The usual way for measuring torque in a wind tunnel is to use a rotary torque sensor. These sensors are very accurate and easy to use. The sensor is connected to the shaft of the turbine on one side and the resistance on the other side. The entire sensor rotates with the turbine. Ideally, this option would be selected, however, these sensors are very expensive, costing anywhere between $4000 and $7000. Ultimately, a solution using a reaction torque sensor was developed. See the "Additional Notes - Power Measurement" section for more details.

IV. WIND TUNNEL MODEL AND TEST PARAMETERS

This hybrid turbine design was intended to be very versatile, excelling in many different environments and applications. The Savonius rotor is a basic rotor that excels in low wind speeds, accepts wind from any direction and provides high torque at low rotational speeds. The Savonius rotor is limited to low rotational speeds and somewhat lower efficiency levels than other rotors. The Darrieus rotor excels in moderate wind speeds, still produces power in low wind speeds, but requires an external source to start the rotation. In the proposed design, the Savonius rotor provides the external assistance needed to jump start the Darrieus rotor. With these ideas in mind, the proposed turbine is an ideal solution for sites with relatively low to moderate wind speeds; sites where large horizontal axis turbines would not be the appropriate solution.

The wind tunnel model was built to have interchangeable parts to test different combinations of design parameters. Two slightly different symmetric airfoil shapes were tested, NACA 0012 and NACA 0015, as well as one cambered profile, S2027 (see Figure 7). Both of the symmetric airfoils were tested with three different chord lengths. These profiles represent the most common airfoil shapes used in previous literature concerning straight-bladed Darrieus rotors. The distance from center to the straight Darrieus blades (Figure 7) and the pitch angle of the Darrieus blades (Figure 9) were also varied.

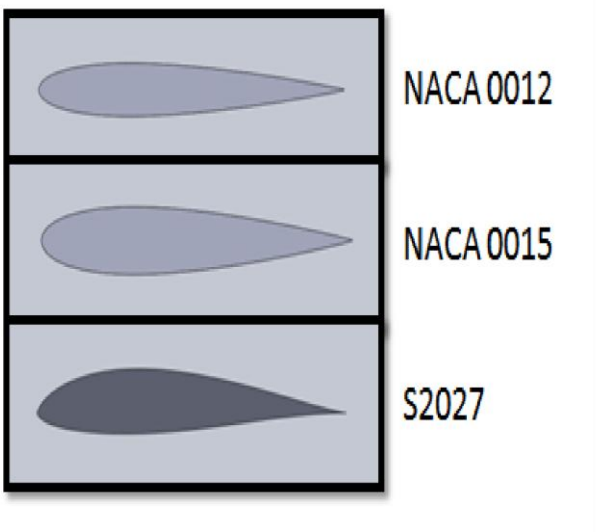


fig 8Turbine model mounted in test stand.

V.EQUIPMENT

RTS Torque Sensor (25 in*oz capacity)

Omron Rotary Encoder (100 pulses per revolution)

National Instruments USB 6009 Data Acquisition System

Labview 8.5Vishay 2120A Strain Conditioner in a Vishay 2100 Mutli-Channel Amplifier

Japan Servo AC Induction Motor

Inspeed Data Logging Wind Speed Anemometer

Bearings / Couplings / Magnets - more information below

Custom-built rotors - more info below

VI.APPLICABILITY

This paper is a starting point for what could potentially be an extremely successful wind turbine design. Because most of the country experiences only low wind speeds, wind turbines optimized for high wind speeds are not effective. More research needs to be done in the low wind speed wind turbine area.

This paper may be particularly interesting to entities that have new projects that are currently not connected to a power grid and have lower power use. This may be an attractive alternative to constructing power lines to the location or having to provide liquid fuel for a generator. This wind turbine design, in conjunction with a battery pack, could provide enough power for the location.

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