21st Australasian Fluid Mechanics Conference
Adelaide, Australia
10-13 December 2018

Analysis of the Chord Overlap and Separation Distance of a 2-Bladed Savonius Wind Turbine

M. Toole, C. Birzer and R. Kelso

School of Mechanical Engineering
Adelaide University, South Australia 5005, Australia

Abstract

The primary aim of this study is to investigate the effects of blade (or chord) overlap and blade separation gap to improve the power coefficient of the system without significant manufacturing changes, such as vanes, wind shields or sails.

The study was conducted experimentally, using a scale model Savonius turbine in a wind tunnel. The torque generated was measured using a commercial generator and software system. These values were measured while varying several characteristics, namely the blade overlap and the wind velocity. The measurements were then used to determine the power generated by the turbine and the drag coefficient of the system. The blade tip velocity was also recorded to determine changes in the tip speed ratio (TSR).

The results indicate that increasing the blade overlap ratio and separation distance ratio beyond 0.15 had a detrimental effect on the output power of the system. This value applies to both the separation distance and blade overlap. The results also indicate that the system performed better when these overlaps were approximately equal. The overlap had a negligible effect on the cut-in speed of the system until the ratio reached approximately 0.3, where the cut-in speed of the system began to decrease due to a change in flow pattern (a much larger amount of air flows between the blades, opposing the starting torque). Finally, the results indicate that increasing the overlap distance in either direction is detrimental to the overall TSR.

Introduction

Savonius turbines were initially designed in 1922, and since then, have undergone continual development to improve their power generation. The most efficient models currently achieve a coefficient of power under 0.35, significantly lower than that of a horizontal axis wind turbine (nearing 0.5). This lower efficiency is generally attributed to the fact that the power generated by Savonius turbines is a function of drag forces, and hence the capture area of the turbine. However, some aspects of the blade configuration, including the relationship between chord overlap (CO) and separation distance (SD), have not been studied sufficiently. The chord overlap ratio is defined as $\frac{CO}{2R}$ and the separation distance ratio is defined as $\frac{SD}{2R}$ as per Figure 1.

Due to their inherently low coefficient of power, but ease of installation and use, most studies have been conducted to improve the power output of the system without sacrificing these positive aspects. A major study in 1978, by Alexander and Holownia [1], investigated a large number of designs with varying parameters, including Reynolds number, bucket configuration, and bucket overlap. This study concluded that a two-bladed system with a blade overlap of 0.1–0.15 was recommended. While this study covered a variety of parameters, the blade separation distance (SD) was left constant throughout.

Ushiyama and Nagai (1988) [8], is one of the few studies found that considers the separation distance between the blades. The study is one of the earlier investigations of Savonius turbines in general, and studied seven different geometric parameters.

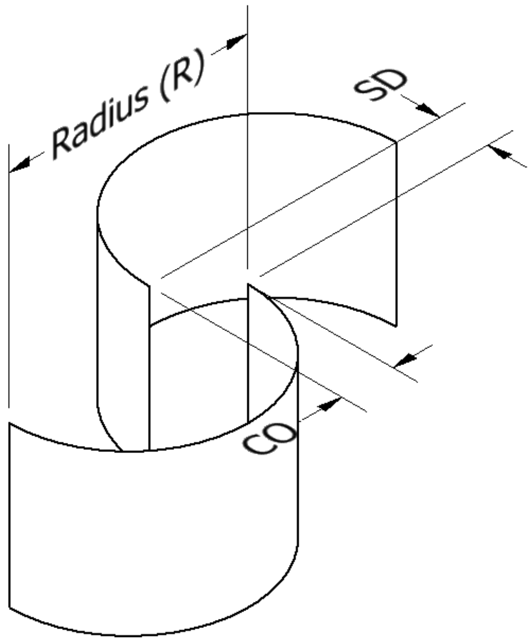

Figure 1: Definitions of Chord Overlap (CO), Separation Distance (SD), and Radius

While this study investigated many physical parameters, it did not study any of these parameters in detail. SD was tested with five different values, and the torque and power coefficient were then compared at different tip speed ratios, up to 1.5. The study found that a slight negative overlap of -0.05 performed best, so that "the air flows increasingly from the advancing bucket to the wake of the returning bucket as the gap separation increases; so the effective drag-force of the advancing bucket decreases." Most modern designs forgo this advice, and turbines are designed with no separation distance. As per Ushiyama and Nagai (1988) [8], the difference in the coefficient of power (C_P) for a chord overlap ratio of -0.05 compared to an overlap of 0 is approximately 0.01 (from 0.23 to 0.22), so the modern manufacturers may see this as a negligible increase. The study did not investigate the change in TSR or cut-in speed changes due to separation distance, nor did they consider changing the blade overlap and separation distance in combination.

More recently, several studies have been published, describing how to improve the range of uses of these turbines. Generally, the aim for these studies is to broaden the application of Savonius turbines: while originally a low velocity flow alternative wind turbine, some are seeing its application as a starter rotor for H-Type Darrieus turbines [3], and the design is also being explored in hydropower [5] and wave energy converters [4]. Bhuyan and Biswas (2014) [3] attempted to combine the starting characteristics of the Savonius turbine with the greater power generation potential of the H-type Darrieus turbine. The study found that the use of a small Savonius turbine co-axial with the H-type turbine had a lower start-up velocity and transitioned between low wind speeds and high wind speeds better. While this study did not analyse the design of a Savonius turbine *per se*, it did identify that the use of a Savonius turbine was broader than originally designed. Dorrell et al. (2010) [4] and Elbatran et al. (2017) [5] show the use of Savonius turbines in complicated configurations to harness the power of waves and in river flows, respectively. While Dorrell et al. (2010) [4] found a conversion ratio (or overall power coefficient) of only 20%, the idea was still novel and, with improvements to the Savonius turbine, could be viable. Elbatran et al. (2017) [5] investigated the use of a ducted nozzle to improve the generation efficiency of a Savonius water turbine. Interestingly, the maximum power coefficient was increased by 78% when compared with the base case. The following study, used in conjunction with Elbatran et al. (2017) [5] and others, may work to improve the overall design and effectiveness of Savonius turbines in a time where the use of renewable energy sources is only becoming more important.

Experimental Method

The research was conducted experimentally using a small-scale Savonius turbine rig in free jet flow in a wind tunnel, using a commercial motor/generator and software package. These provided measurements that were then used to determine the power generated by the turbine and the power coefficient of the system. The experiments were conducted at a Reynolds numbers ranging from 204,000 to 289,000, based on the diameter of the turbine. Due to the electrical efficiency data of the generator not being available, the mechanical drag coefficient of the turbine was unable to be determined. This commercial generator also causes the coefficient of power to be unexpectedly low, although this low coefficient of power does not affect the results in any significant way. The Savonius rig was designed to have variable blade chord overlap and separation distance, to determine the effects of geometric changes on the cut-in speed, tip speed ratio (TSR) and power coefficient at a range of wind speeds.

To determine the coefficient of power (C_P) for a given system layout, the power potential in the wind has to be defined. The coefficient of power is generally defined by the following equation:

$$C_P = \frac{P_{OUT}}{P_{IN}} \tag{1}$$

where P_{OUT} is a measured value from the generator system, and P_{IN} is defined as

$$P_{IN} = \frac{1}{2}\rho h D V^3. \tag{2}$$

Here, ρ is defined as the density of air [kg/m^3], h is the height of the blade [m], D is the nominal diameter of the blade [m] and V is the free-stream velocity of the wind generated by the wind tunnel [m/s].

The tip speed ratio (TSR) of each system layout is the other derived value being investigated in this study. The TSR is defined as the ratio between the tangential speed of the blade tip and the free-stream speed of the wind generated by the wind tunnel, or:

$$TSR = \lambda = \frac{\text{Tip Speed}}{\text{Wind Speed}} = \frac{\omega R}{V}. \tag{3}$$

Here, ω is the measured angular velocity of the blade (rad/s), R is the distance between the centre of the turbine and the tip of the blade (which changes based on the overlap) and V is defined above.

The model was mounted on a horizontal plate 400mm from the 0.9m by 0.9m octagonal nozzle exit of the wind tunnel, at which location the boundary layer thickness on the floor was under 10mm [6], so the effects of boundary layer are minimal and were ignored.

The Savonius turbine has nominal dimensions of $h = 300$mm, and $D = 300$mm, for the case of zero overlap in either direction, so the actual diameter of the turbine changes throughout testing. This gives a nominal blockage ratio of approximately 14%. According to Barlow, Rae and Pope (1999) [2], the effects of blockage on an open-jet wind tunnel are approximately $\frac{1}{4}$ of those in a closed section, bringing the effective blockage in this case to 3.5%. The blades have a simple semicircular shape that remained constant throughout testing. The Savonius rig is made of stainless steel with an acrylic plastic base. This base housed the generator/motor system, designed and sold by Heliocentris. The separation distance and blade overlap were varied from 30mm to 60mm, or in terms of a ratio, from 0.1 to 0.2.

Results

The initial tests were undertaken at a constant separation distance (SD) of 30mm, or a separation distance ratio of 0.1. The results of these tests can be seen in Figure 2. This graph clearly indicates that over the tested velocity range ($2.5 - 4$m/s), the 30mm chord overlap (CO) configuration has significantly better results, implying that increasing the chord overlap has a detrimental effect on the coefficient of power and power output. This is partially due to the reduction in surface area, since increasing the overlap decreases the distance between each blade tip, thus reducing the area. The increased overlap also has a negative effect on the flow characteristics of the system, becoming more pronounced at overlap ratios $> 30\%$. This first graph implies that a lower chord overlap ratio ($\frac{CO}{2R}$) is always desirable until 0.1-0.15, the optimal range given in Alexander and Holownia, (1978) [1]. The chord overlap distances of 30mm and 40mm lie within this optimal range.

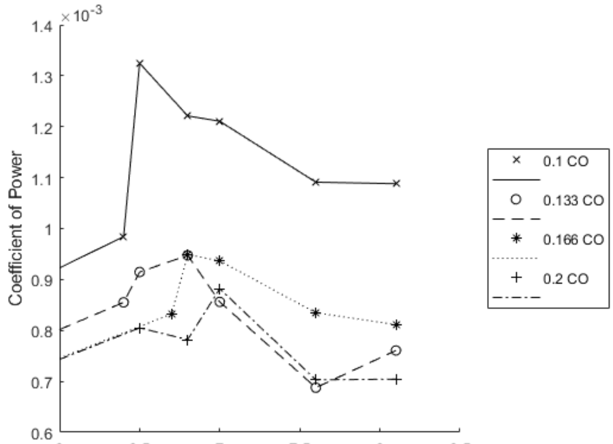

Figure 2: Coefficient of Power vs. Wind Speed for 0.1 Separation Distance Ratio and a range of Chord Overlap Ratio values.

Figure 3 shows the results of the same tests as presented in Figure 2 except at a 45mm separation distance. In this figure the relationship between chord overlap and power output is less clear. Overall, the system had similar but less consistent power output characteristics, with all tested chord overlap distances falling in a similar range. This indicates that at higher separation distance ratios the relationship between chord overlap and power output becomes less important. Since increasing the overlap beyond 0.2 has significantly detrimental effect on the cut-in speed of the system (discussed below), this conclusion about separation distance, while novel, is largely unimportant.

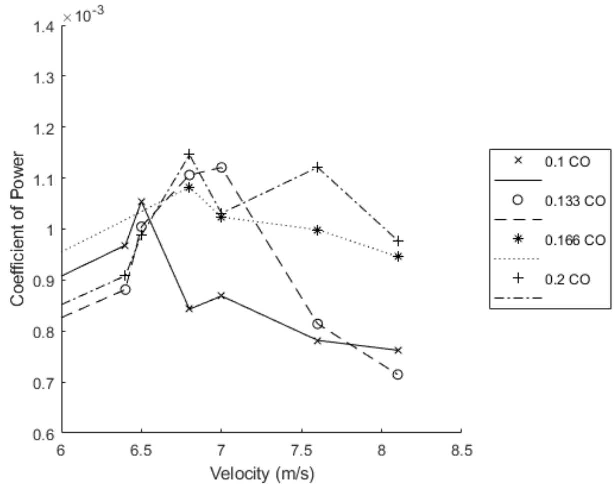

Figure 3: Power vs. Wind Speed for 0.15 Separation Distance Ratio and a range of Chord Overlap Ratio values.

When compared to the previous figures, Figure 4 has a significantly smaller data set. This is due to a much higher cut-in speed caused by the larger separation gap. The larger separation gap creates an issue for a large arc of the system's rotation, where the two blades are "separate," in the sense that they do not interact with each other to generate power. While both blades continue to produce drag, they act independently. This causes the turbine to generate less torque and subsequently less power. As a result, these blade configurations have a small operating range at low velocities.

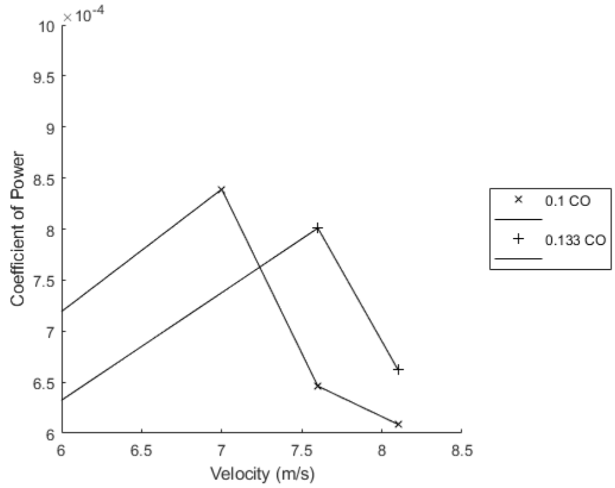

Figure 4: Power vs. Wind Speed for 0.2 Separation Distance Ratio and a range of Chord Overlap Ratio values

The results of this section indicate that reducing the separation distance is preferable for this range of velocity and chord overlap. Results at other chord overlap ratios were compared that implied the same outcome [1, 8].

The final section of results will discuss the tip speed ratio of the system and how this ratio changes depending on the chord overlap and separation gap. Figures 5, 6 and 7 shows the effect of TSR on the coefficient of power. For these tests, the generator torque was controlled to vary the rotational speed for the system. Figure 5 indicates that a low chord overlap is preferable, with the optimal TSR of the system occurring at 0.4, with a corresponding coefficient of power of 0.026. This is consistent with previous research into the relationship between TSR and the coefficient of power, Le Gourirs, (1982) [7]. The actual mechanical power coefficient is unable to be determined, however, the ratio between TSR and C_P can be analysed. Consistently across all three figures, the negative chord overlap leads to a lower maximum power coefficient but tends to operate at a wider range of tip speed ratios. This behaviour can be attributed to the larger radius for the system. This effect is useful when a system is required to provide torque over a large range of wind speeds, but the actual power generated need not be high — for example, when used as a starter for a mixed Savonius-Darrieus turbine system, such as in Bhuyan and Biswas (2014) [3].

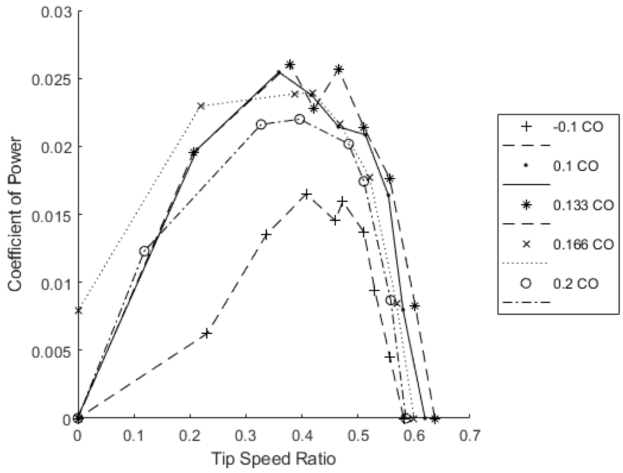

Figure 5: TSR for a range of Chord Overlap configurations with constant Separation Distance ratio of 0.1

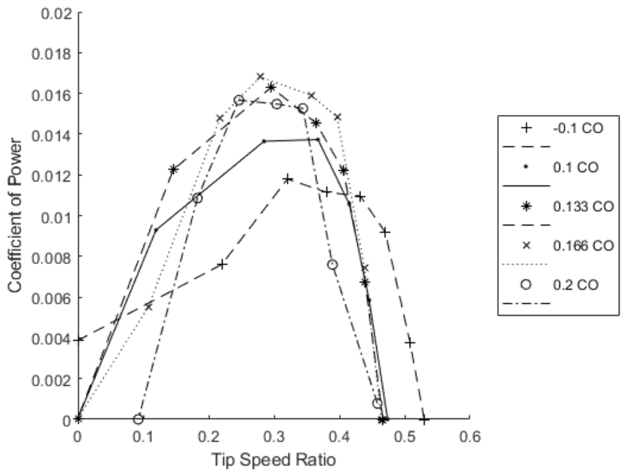

Figure 6: TSR for a range of Chord Overlap configurations with constant Separation Distance ratio of 0.15

Comparing figure 5 and 6 indicates that increasing the separation distance generally has a detrimental effect on the relationship between TSR and C_P. However, when the CO and SD of the system are equal or near equal, the system has a higher average coefficient of power. This is due to the symmetry of the system being maintained, since at extreme chord overlap or separation distances, the turbine shape is elongated more than usual in the respective direction. The power coefficient of a Savonius turbine fluctuates naturally due to its shape, but extreme overlaps cause the power output to fluctuate more significantly and contribute to an overall lower coefficient of power. These lower values of blade overlap and separation distance also fall within the range stated by Alexander and Holownia, (1978) [1]. This effect is seen in both figures 6 and 7.

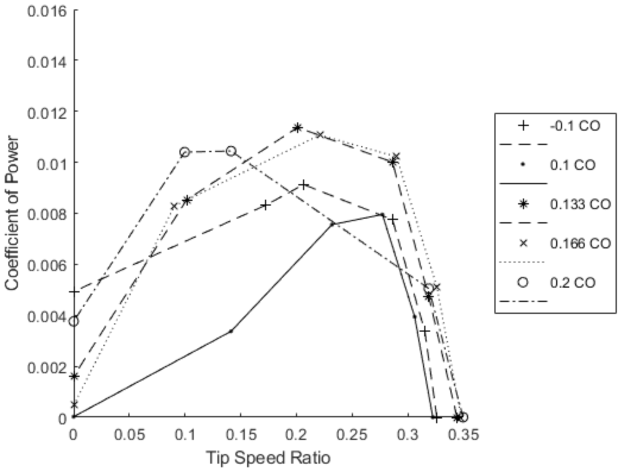

Figure 7: TSR for a range of Chord Overlap configurations with constant Separation Distance ratio of 0.2

Conclusions

This research has investigated the change in power output of the traditional Savonius turbine by varying the blade overlap and separation distance. These values were tested over a range of overlap ratios, and the performance changes as well as changes in several turbine characteristics such as the TSR and cut-in speed have been studied. The following conclusions have been gathered from the research:

- Blade spacing in the chord-wise direction (CO) has a detrimental effect on the power output, with increased spacing causing a decrease in power, which is consistent with previous results. The system with the greatest coefficient of power was the system with the lowest chord overlap and separation distance.
- Blade spacing in both the chord- and span-wise direction has a negative effect on the power output of the system when compared to the base case. Over the range of spacing tested, greater spacing almost always had a detrimental effect on the power output.
- The blade spacing configurations had a mixed effect on the TSR of the system. For a low separation distance, increased chord overlap reduced the tip speed ratio. On the other hand, when the chord overlap and separation distance are near equal, the system produces a higher average coefficient of power. Further work is recommended to better understand the mechanism leading to this observation.
- Generally, the cut-in speed of the system remained unchanged until very high separation and chord overlap ratios, (0.2 or greater) where they began to decrease rapidly.

It is concluded that increased separation distance and chord overlap are not recommended for improving starter characteristics of Savonius turbines, except in cases where the separation distance and chord overlap are near equal.

Acknowledgements

The first author gratefully acknowledges the funding received from the federal government under the Research Training Program. The authors also thanks the University of Adelaide for providing facilities throughout the study.

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