Performance characteristics of the Savonius turbine

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Abstract. The paper presents performance investigation of the Savonius turbine both in terms of starting and power extraction characteristics. Effects of the number of blade and the overlap ratio were investigated experimentally using a wind tunnel at a wind speed of 4.45 m/s. Results show that the number of blades and the overlap ratio have a great impact on both performances. In terms of starting, the two-bladed rotor was found to be able to produce higher peak torque than the three-bladed case. However, the three-bladed rotor has a greater starting capability due to its more continuous torque production. The overlap ratio was found to reduce the amount of torque and hence their starting performance. With regard to power extraction characteristic, the three-bladed rotor without the overlap ratio was found to exhibits the highest performance.

1. Introduction
The Savonius turbine was invented by the Finnish Engineer, Sigurd Johannes Savonius, in 1922 [1]. It is categorized as a drag type machine as the incoming wind will ‘drag’ the blade to spin around its vertical axis (figure 1). The drag force caused by the incoming wind actually acts on both sides of the rotor blade. The force on the convex side is however higher than that of the concave side and this causes a net force that drive the rotor (figure 2).

![Figure 1. The Savonius turbine](image-url)
Many tests were conducted focusing on power extraction performance [2-4] and little work had been done to investigate its starting characteristics [5, 6]. For example, Saha et al [2] conducted some tests to evaluate aerodynamic performance of Savonius rotors with different stages. Tests conducted by Ali [3] showed that two-bladed rotor has a higher power coefficient than the three-bladed rotor and the author reasoned that the three-bladed configuration has a higher drag at the operating condition. Typically, the Savonius turbine will operate at the tip speed ratio of around 1 and has a power coefficient of about 0.15 (figure 3).
Starting characteristic of this type of turbine is however not investigated in greater detail. Measurement of static torque of semi cylindrical blades together with flow visualization were conducted by Sawada et al [5]. The measurement had shown that the static torque varies continuously over the azimuthal angle but had not shown that how that static torque affects the starting behavior of the turbine. In addition, the tests were also conducted at a very low wind speed of 15 cm/s. A more detail study was made by Ushiyama et al [6]. In this study, wind tunnel tests on a model which was made of steel sheet was conducted. A number of design parameters such as aspect ratio and overlap ratio were systematically investigated. The investigation revealed that, for the semi cylindrical blade, the two-bladed rotor with zero gaps and the overlap ratio of 0.2 is the optimal configuration.

It is worth noting that the rotor investigated in the previous research was made of steel, which is heavier than other materials such as aluminum and carbon fiber. With an application of lighter materials, the optimal configuration may be significantly changed as the rotor inertia can be reduced. The understanding of this starting characteristics with appropriate rotor materials is of importance as recent research had shown that the improvement of starting characteristic will increase the turbine operating range and can lead to a significant amount of power output [8].

This paper then experimentally investigates starting and energy-extraction characteristics of the aluminum-made Savonius rotor in order to figure out an optimal configuration. A number of parameters such as number of blades and overlap ratio, which governs the generation of torque, were investigated.

2. The Savonius Rotor

The Savonius rotor employed in this study is configured to be 36 cm width and 45 cm height. It consists of rotor blades that are covered by end plates at the top and the bottom (figure 4). The blades are semi-circular of 15 cm diameter and made of aluminum. The end plates are laser-cut and also made of aluminum. The whole rotor set is attached to a vertical metal shaft which is held by a tower that sits on a stand.

Figure 4. Example of the Savonius rotors

The rotor end plates were laser-cut in such a way that the rotor configuration such as number of blades and the overlap ratio can be easily varied. For example, they were laser-cut radially with a series of holes and the change of the overlap angle can be easily achieved by selecting different radial positions. This study however is limited to two and three blades and one set of the overlap ratio. All tested configurations are presented schematically in figure 5 and table 1 summarizes specification of all rotors.
Figure 5. Two and three bladed rotors with and without the overlap angle

Table 1. Rotor Configurations.

| Rotors | No. of Blades | Overlap Ratio (%) | Blade Width (cm) | Diameter (cm) | Height (cm) |
|--------|---------------|-------------------|------------------|---------------|-------------|
| S1     | 2             | 0                 | 15               | 36            | 45          |
| S2     | 2             | 10                | 15               | 24            | 45          |
| S3     | 3             | 0                 | 15               | 36            | 45          |
| S4     | 3             | 10                | 15               | 24            | 45          |

3. Testing Facility and Procedure
The wind tunnel used for the experiments was an open-jet type which discharges directly to the atmosphere (figure 6). It has a working section of 0.8 x 0.7 m. Turbulence intensity was found to be 3.5% at the maximum wind speed of 4.45 m/s. The turbine was installed on a stand in front of the tunnel exit (figure 6).
Starting torque measurement was conducted using a Futek torque sensor. In every measurement, the rotor will be set at a reference point (the azimuthal angle of zero as shown in figure 7). After the measurement completed, the rotor will be rotated counterclockwise by 10 degree to measure starting torque at the next azimuthal angle. This process continues until it completes the revolution. This test was conducted at a wind speed of 4.45 m/s.

Starting behavior of the rotor also performed at the wind speed of 4.45. In this kind of test, the tunnel will be turned on and the rotor was held stationary. After the wind speed stabilized, the rotor was released and its rotational speed was recorded at a sampling rate of 1 Hz.

Power measurement was also conducted using the Futek sensor by applying a known load to the other end of the torque sensor (figure 8). With this load, the strain gauge senses a net torque that the rotor has to exert to spin the load and a rotational speed that the whole turbine spins at the same time. Power of turbine is the product of the two measured quantities.
4. Results

4.1 Starting Torque

The starting torque of the two-bladed rotors as a function of the azimuthal angle are presented in figure 9.

![Figure 9](image)

Figure 9. Starting torque: two-bladed

It can be seen that starting torque of the two-bladed rotor is around 0.077 Nm at the reference angle. The torque roughly decreases with the increasing azimuthal angle (as the rotor moves away from the incoming wind) until reaches its lowest value of 0.008 Nm at the azimuthal angle of 60. After that, it increases to the peak of 0.15 Nm at the azimuthal angle of 80 and then reduces as the rotor moves to 180 degree at which the same pattern is repeated. The azimuthally averaged torque of the rotor was found to be 0.083 Nm.
The torque distribution over the azimuthal angle is significantly affected by the incorporation of the overlap ratio, as seen in figure 9. The amount of torque at the reference angle is reduced to 0.015 Nm, compared to 0.077 Nm and this is anticipated to be the result of reduced swept area that shorten the effective area of the rotor blade (figure 10). This results in a reduction of torque over the azimuthal range (figure 9). The average torque is then decreased to 0.039 Nm.

![Figure 10. Effect of overlap angle on swept area and net force](image)

The peak of the torque is however less observed in the three-bladed configurations (figure 11). For three-bladed rotor without the overlap angle, the torque value is about 0.027 Nm at the reference point. It is worth noting that this stating torque is lower than that of the two-bladed one and this is thought to be the effect of interference between blades. The maximum torque is reduced to 0.1 Nm and the average torque over the revolution is 0.076 Nm. In this scenario, the airflow will be diverted by the nearby blade. This effect increases when the blade further move away from the incoming wind as shown in figure 12. Although the two-bladed configuration can generate higher torque, it is subjected to a periodic pulsation which will lead to bearing failure.

![Figure 11. Starting torque: three-bladed](image)
Comparison of torque distributions of the two- and three-bladed rotors in figure 9 and 11 shows that, although the maximum torque of the three-bladed rotor is lower than the two-bladed case, its torque distribution is comparatively flat and does not experience a large drop to a nearly zero value at the azimuthal angles between 130-180, as presented in the two-bladed cases. The incorporation of the overlap ratio again reduces the overall torque generation of the rotor.

4.2. Starting Behavior

Figure 13 compares starting characteristic of the two-bladed rotors and it can be observed that the two-bladed rotor can accelerate to its final rotational speed of around 150 RPM. The incorporate of the overlap ratio, however, decreases the rotor ability to start and the rotor can accelerate to around 110 RPM and takes about 120 seconds to reach its final rotational speed. This reduced performance is the effect of the overall change of the swept area of the rotor that reduced the amount of incoming wind that strike on the rotor blade (figure 10). In addition, the overlap ratio also change the radius of the resultant force on the blade, resulting in a significant reduction of the torque and the degradation of starting capability.
Similar behavior was found in the three-bladed case (figure 14). The incorporation of the overlap ratio significantly affect the turbine ability to start, especially the time that the rotor takes to reach the final rotational speed. While the three-bladed rotor takes 70 seconds to reach the final RPM, the rotor with the overlap ratio takes up to 200 seconds to reach its equilibrium. The final, operating RPM is reduced from 190 to around 150. It is worth noting that the optimal configuration in this study was found to be three-bladed configuration rather than two-bladed configuration as shown by Ushiyama et al [6]. This implies that, with the use of lighter material, the addition of the third blade will not increase the rotor inertia significantly and can promote the ability to start despite generating lower torque.

![Figure 14. starting characteristic: three-bladed rotors](image)

4.3. Cut-In Speed
With the starting behavior characteristics in the previous section, it is interesting to explore what cut-in speed that each rotor begins to start spinning. This investigation was conducted by increasing the inverter frequency by 5 Hz and rerun the test until the rotor begins spinning and be able to sustain that spinning to a particular rotational speed. It is however worth noting that the torque sensor used in this study has a significant amount of friction and this inevitably hinders the starting of the turbine. The results then compare the effect of rotor configuration on the cut-in speed qualitatively. The real cut-in speeds were not obtained from this kind of measurement. Figure 15 shows the results.

![Figure 15. Cut-in wind speed](image)
It can be observed from the figure that the 3 bladed rotor without the overlap ratio has the lowest cut-in wind speed of 3.5 m/s. This characteristic is closely related to the starting torque characteristics of the rotor that the 3 bladed rotor manage to produce a more continuous torque. As expected, the incorporation of overlap ratio, which reduces the rotor swept area and the radius of the net force, causes the rotor to be more difficult to spin and needs a higher wind speed to be able to start.

4.4. Power

Since the three bladed rotor without the overlap ratio has the best performance characteristics, only power coefficient of this turbine is shown. Figure 16 presents its power coefficient as a function of tip speed ratio and

![Power coefficient](image)

It can be seen from the figure that the turbine has a maximum power coefficient of 0.125 at a tip speed ratio of 0.79. This maximum power coefficient is lower than the generic performance presented in figure 3 and occurs at a lower tip speed ratio (0.79 compared to around 1 in figure 3). This is anticipated to be the effect of the tested wind speed which is comparatively low. The low wind speed typically lowers the tip speed ratio that the turbine operates and also its power coefficient.

5. Summary

The performance characteristic of the Savonius turbine was experimentally examined and the following conclusions are found:

- The number of blades has a great impact on the starting characteristic. Three bladed rotor will always produce a more continuous torque, on both with and without the overlap ratio.
- The overlap ratio generally reduces the torque generated by the turbine and hence its starting capability, as the swept area is smaller.
- The use of lightweight materials is beneficial and the optimal configuration might be different if different materials are used.
- Of investigated, the three-bladed rotor without the overlap ratio exhibits the highest starting capability and power extraction performance.
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