Effect of twist angle on starting capability of a Savonius rotor – CFD analysis

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Abstract. Starting capability is an important feature of any high performance wind turbine. This parameter is usually referred to the rotor static performance. In this paper, the results of CFD analysis on four Savonius rotor designs are presented with the objective of investigating the effect of twist angle on the starting capability. Essentially it is a comparison between a conventional Savonius rotor and three helical rotors with 0°, 90° and 180° twist angle. The proposed methodology was first validated against the published wind tunnel test data. The best parameters were then used to evaluate the static performance of the four Savonius models. It is observed that helical Savonius rotor contributes to positive static torque coefficient for all rotor angles. The rotor with 90° twist angle gives the highest average static torque coefficient of 0.442 followed by 0° twist angle rotor and 180° twist angle with static torque coefficient of 0.434 and 0.385 respectively. This improvement in static torque coefficient will not only contribute to the better starting capability but also to the overall performance of Savonius rotor.

1. Introduction
Despite having a low power efficiency of less than 0.15, Savonius rotor has proven to be well suited for low speeds or urban applications. In many Southeast Asian counties like Malaysia, where the average wind speed is rather low (about 2 m/s) Savonius-solar system may be adopted in order to generate a useful and reliable electric power. In other parts of the world, many studies have been carried out in an attempt to increase the performance of a Savonius rotor. These include the addition of end plates, incorporation of offset, aspect ratio, bucket angle and twist angle [1]. To this end, power coefficient of exceeding 0.5 has been achieved with the addition augmentation device such as deflecting plates [2]. In addition to this, power enhancement has also been made possible via multiple rotor clusters approach [3].

Irrespective of turbine design either Horizontal Axis Wind Turbine (HAWT) or Vertical Axis Wind Turbine (VAWT), starting capability is one of the important criteria for designing high performance Savonius rotors. It is the ability of a wind turbine to start generating power at any initial azimuthal position for given wind speed. This definition may, however, differ from others [4]. A turbine with this capability should, therefore, be able to self-start at relatively lower wind speed as it has lower cut-in wind speed [5]. Ease of starting is highly dependent on its static torque. Higher average static torque means the better is its starting capability. Savonius rotor has the reputation of having such a good self-starting capability. An introduction of twist angle and gap ratio to Savonius blade design resulted in a positive coefficient of static torque for all rotor angle and thus improving the starting capability. Wind
tunnel tests performed by [6, 7] revealed that helical Savonius with twist of 90° and 180° can overcome the drawback of negative torque. Augmentation techniques such as guide box tunnel, guide vanes, obstacle plate, frontal nozzle, and frontal guiding plates can improve the static torque by 35% and up to 50% but only suitable for a certain condition such as small operating range and at specific orientation for wind direction. Other factors influencing the starting torque include blade shape optimization [8]. Starting capability of Savonius is generally evaluated by CFD simulation and followed by validation via wind tunnel experiment. The accuracy of such an analysis completely dependent on parameters such as grid size, domain size, turbulence model, azimuthal increment, number of revolution to reach convergence [9].

The main objective of the present study was to study the effect of twist angle on the Savonius rotor starting capability through CFD analysis. The proposed methodology was first validated against the published wind tunnel test data. Torque coefficients for different Savonius rotor models were then compared. This study used a commercial computational fluid dynamics solver called AcuSolve.

2. Validation of the methodology and Savonius rotor model
The reference model for the validation is obtained from the published experimental data [10]. The main objective of this exercise was to compare the predicted static torque coefficient results with the former. Minimum error is achieved when the selected parameters are optimized.

2.1. Rotor validation model
The design parameter was graphically shown in figure 1 and summarized in table 1.

![Figure 1](image1.png)

**Figure 1.** The reference Savonius rotor model showing different views: (a) Top (b) Front (c) Isometric.

**Table 1.** Design parameter for validation model.

| Parameter          | Value | Unit |
|--------------------|-------|------|
| Height, H          | 1     | m    |
| Diameter, D        | 1     | m    |
| End plate diameter, D₀ | 1.1D  | m    |
| Number of buckets  | 2     | -    |
| Aspect ratio, H/D  | 1     | -    |
| Overlap ratio, δ   | 0     | -    |
| Twist angle, φ     | 0°    | Degree |

2.2. Helical Savonius rotor model
Three helical Savonius rotors with different twist angles used in this study are as shown in figure 2. Each rotor has common dimensions: H = 1 m, D = 0.5 m with δ (e/d) = 0.242 and D₀ = 1.1D.
3. Numerical analysis

The 3D computational domain with the dimension of 30D x 16D x 16D was used in this study [11]. The static Savonius rotor was placed in the center of the domain. A steady flow of 7 m/s was set at the inlet. The experiment was repeated using different turbulence models namely Spalart-Allmaras (S-A), SST and K-ω. The boundary conditions (BC) are shown in figure 3.

![Figure 3. BCs assigned to 3D-computational domain.](image)

The static analysis was carried out in order to evaluate the rotor performance at still condition focusing on torque generated by the rotor [12]. The static position of the Savonius rotor was initially placed as in figure 1 (a) position, θ. The rotor position was changed at 10° interval [10]. 19 models of Savonius static position were required in order to complete one half-rotation. The static torque was calculated at every position and compared finally with the available wind tunnel data. The static torque coefficient, $C_{ts}$ was calculated by using equation (1).

$$C_{ts} = \frac{4Ts}{\rho V^2 D^2 H}$$  \hspace{1cm} (1)

where $Ts$ is the rotor static torque at $\theta$ rotor position (N.m), $\rho$ is the air density (kg/m3), $V$ is flow stream velocity (m/s), $D$ is rotor diameter (m) and $H$ is rotor height (m).

Grid or mesh sensitivity study was conducted to evaluate the effects of the mesh size on the analysis result. The mesh was refined to a certain boundary, and result from the analysis was observed. Each mesh size was solved using Acusolve based on the same input parameter. Further refinement will not give a significant effect on the analysis result [13]. Several meshing sizes of tetrahedral shape were utilized to increase the mesh density and mesh quality. Sufficient mesh density was selected and generated in the region of high-pressure gradient around the rotor profile. In this study, three mesh sizes were selected. Mesh #1 setting consists of elements 20164721. Whereas Mesh #2 and mesh #3 generated 5229713 and 253365 number of elements respectively. The boundary layer was set around the rotor and adaption of $y+$ value of 1 for enhanced wall treatment [14].

The selected parameter setting from CFD validation was then used to evaluate the proposed helical Savonius rotor designs. The input wind velocity is set as Cartesian velocity with a uniform value of 3 m/s.
4. Results and discussion
The static analysis used to explore the Savonius rotor static performance which contributes to the explanation of rotor self-starting term [5].

4.1. Mesh sensitivity study
Figure 4 shows the static torque coefficient at variation of rotor angle for tested mesh sizes. The mesh density increases with the mesh setting from mesh #1 to mesh #3. As expected an increase in the number of elements increases the computational time.

The results show similar patterns as observed by the wind tunnel test data [10]. Coarse mesh denoted by mesh #1 shows predicted torque coefficients are close to the experiment for rotor angle between -35° to 65° but starts to deviate after rotor angle 75°. Medium mesh represented by mesh #2 shows a good agreement with the wind tunnel data. However fine mesh #3 shows a large deviation from the experimental data.

![Figure 4. Mesh sensitivity results.](image)

4.2. Turbulence model sensitivity study
The numerical study results of turbulence model investigation are presented in figure 5. The SA turbulence model provides a fairly good estimate to those data obtained by the experiment. However, the SST and k-ω turbulence models are seemed to have overestimated and underestimated the static torque at certain rotor angles. Therefore, all CFD analysis for the four proposed models were performed based on the SA turbulence model.

![Figure 5. Sensitivity analysis of turbulence models.](image)
4.3. Effect of twist angle on static torque coefficient

Figure 6 shows static torque coefficients generated by the reference (conventional) rotor and three other rotors with twist angle at different rotor angles.

![Figure 6. Static torque coefficient for different rotor design.](image)

The conventional Savonius rotor experiences a low and nearly zero torque coefficient at certain rotor angles and thus revealing its unlikelihood to rotate at those rotor angles. Additional end plate and adaption of overlap ratio as depicted by 0° twist angle seems to slightly increase the static torque coefficient. The helical Savonius rotor with twist angle 90° and 180° show a great improvement in the static torque coefficient variation. It is also observed that the average static torque coefficient for conventional Savonius rotor and proposed Savonius rotor with additional of end plate, adaption of overlap ratio with twist angle of 0°, 90° and 180° are 0.25, 0.434, 0.442 and 0.385 respectively.

5. Conclusions

Conclusions derived from this study are as follows:

a. The validation process initially taken in this study shows that the proposed evaluation methodology is acceptable.

b. The Spalart-Allmaras (SA) turbulence model adopted in superior in terms of accuracy when compared to other models.

c. The helical Savonius rotor with endplate and overlap ratio shows a low variation of static torque coefficient at various rotor angles. In fact, it can overcome the drawback of negative and nearly zero static torque coefficient experienced by a conventional Savonius rotor.

d. The best static torque performer of this study is the helical Savonius with 90° twist angle where the static torque coefficient obtained is 0.442. This finding is fairly similar to [6].

Acknowledgments

The authors would like to acknowledge the Malaysian Electricity Supply Industries Trust Account (MESITA) through the Ministry of Energy, Science, Technology, Environment & Climate Change (MESTECC) for funding this research.

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