The influence of main blade length on the efficiency of the optimized multi-curve Savonius wind turbine

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Abstract— In this study, a numerical investigation is carried out to assess the impact of the main blade length on the efficiency of the optimized multi-curve Savonius wind turbine. The simulation utilizes an unsteady 2D computational fluid dynamics sequence by the commercial software ANSYS Fluent 2021R2. The results indicate that the length of the main blade has a significant impact on the rotor performance. The highest performance of the rotor in this investigation is recognized with the main configuration made by a 0-degree cut angle section and a quarter elliptical section. This peak power coefficient has been obtained by 99.13% at a tip speed ratio (TSR) of 1.4 when compared to Blackwell’s experimental data of the original configuration before decreasing at higher TSRs.

Keywords— Savonius, multi-curve, tip speed ratio, Realizable k-ε.

I. INTRODUCTION

Savonius turbine is a vertical axis wind turbine, characterized by its self-starting behavior and its ability to operate independently to wind direction. This rotor can be favorably installed in both rural and urban areas thanks to its characteristics, such as omnidirectional operation, low starting speed, affordable operating costs [1, 2], easy installation and maintenance. Additionally, the noise level during operation from these rotors is relatively low due to their small size, and therefore, is less annoying to the nearby regions. Yet, the performance of the conventional Savonius turbine with two semicircular blades, in terms of power coefficient ($C_p$), is still relatively low compared to other turbines.

A lot of researches have been published so far to improve and find ways to optimize performance of Savonius rotors, including navigating the flow using deflectors [3-4] and modifying the blade configurations [5-13]. With the first method, these deflectors can effectively redirect the flow toward the advancing blade while simultaneously preventing it from reaching the returning blade to increase the performance of the rotor. However, this technique makes the turbine system complex and dependent on wind direction. Currently, researches are carried out mostly to optimize blade configurations, such as modified overlap blades [5], various thickness blades [6, 7], Bach-blades [8-10], and elliptical blades connected to multi-curve blades [11-13].

Depending on different configuration improvements, the power coefficient ($C_p$) of the Savonius rotor can increase by a few to a hundred percent. However, the application efficiency in rural and urban areas of these studies is not high because they only focus on improving in low TSRs below 0.8.

Our recent study introduced a new improved blade configuration, which is a combination of a semicircular blade and a quarter of an elliptical blade [11]. This study has also led to the conclusion that the new blade configuration works competitively in high TSRs because it greatly reduces flow separation. The results showed that the power coefficient improved up to 99.13% at TSR 1.4 on improved blade configuration, perfectly suitable for urban and rural wind energy applications. In another of our studies, changing the semicircular configuration to a multi-curve blade configuration was shown to significantly improve the performance of this configuration type ($C_p$ up to 185.1% at TSR 1.5) [12]. This shows that the change of the main blade configuration also significantly affects the performance of the improved blade rotors.

This study was conducted to investigate the effect of the main rotor length on the performance of the multi-curve Savonius wind turbine. A variety of blade configurations with different main blade lengths, determined by the dimensionless parameter $\beta$, were studied to find the configuration with the best performance. In this study, the
evaluation analysis was conducted utilizing unsteady simulation by commercial software ANSYS Fluent 2021R2.

II. GEOMETRIC CONFIGURATIONS

Fig. 1 shows the configurations of the modified multi-curve Savonius rotor, as for Anh et al.'s study [12], and design parameters based on the original design by Blackwell et al. [14]. The detailed designed parameters for original and adjusted rotor configurations are illustrated in Table 1. As for the adjusted rotor configurations, the length of the main configuration is characterized by the cut angle parameter \( \beta \). Here, the adjusted rotor configurations are named A-30, A0, A30, A60, and A90 which are proportional to the \( \beta \) ranging from -30° to 90°, respectively. In this study, the effect of the different \( \beta \) parameters is numerically investigated.

Fig. 1. Geometry and parameters of rotor configurations (a - f)

TABLE I. DETAILS OF ROTOR CONFIGURATION DESIGN PARAMETERS

<table>
<thead>
<tr>
<th></th>
<th>( d ) [m]</th>
<th>( D ) [m]</th>
<th>( t ) [m]</th>
<th>( h^* )</th>
<th>( R_1^* )</th>
<th>( R_2^* )</th>
<th>( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>0.5</td>
<td>1</td>
<td>0.004</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-30</td>
<td>0.5</td>
<td>1</td>
<td>0.004</td>
<td>0.25</td>
<td>0.5</td>
<td>0.55</td>
<td>-30°</td>
</tr>
<tr>
<td>A0</td>
<td>0.5</td>
<td>1</td>
<td>0.004</td>
<td>0.25</td>
<td>0.5</td>
<td>0.55</td>
<td>0°</td>
</tr>
<tr>
<td>A30</td>
<td>0.466</td>
<td>1</td>
<td>0.004</td>
<td>0.25</td>
<td>0.5</td>
<td>0.55</td>
<td>30°</td>
</tr>
<tr>
<td>A60</td>
<td>0.375</td>
<td>1</td>
<td>0.004</td>
<td>0.25</td>
<td>0.5</td>
<td>0.55</td>
<td>60°</td>
</tr>
<tr>
<td>A90</td>
<td>0.249</td>
<td>1</td>
<td>0.004</td>
<td>0.25</td>
<td>0.5</td>
<td>0.55</td>
<td>90°</td>
</tr>
</tbody>
</table>

III. NUMERICAL SIMULATION

A. Numerical method

The unsteady simulation used in this study is employed by the commercial CFD program ANSYS Fluent 2021R2. The flow around the Savonius rotor is examined by solving the 2D incompressible Reynolds Averaged Navier-Stokes equations (RANS) as follows [11]:

\[
\frac{\partial \bar{u}_i}{\partial x_j} = 0 \tag{1}
\]

\[
\frac{\partial \bar{p}}{\partial t} + \frac{\partial}{\partial x_j}\left(\bar{\rho}\bar{u}_i\right) = \frac{1}{\rho} \frac{\partial}{\partial x_j}\left(\bar{\rho} \bar{u}_j\bar{u}_i - \bar{\rho}\bar{u}_i\bar{u}_j\right) \tag{2}
\]

Here, \( \bar{p} \), \( \bar{\rho} \), \( \bar{u}_i \), \( \bar{u}_j \) represented the pressure, mean velocity, fluctuation velocity, and the kinematic, respectively. The Reynolds stress tensor was symbolized by \( \bar{u}_i \cdot \bar{u}_j \). In order to consider the effects of turbulence on the flow around the rotor, the realizable \( k - \varepsilon \) turbulence model and the enhanced wall function are selected [11].

The implicit pressure – velocity coupling algorithm, the least-square cell-based scheme for the spatial discretization of the gradient, and the second-order upwind scheme for the temporal/spatial discretization are used to solve the governing equations. To simulate the rotation of the rotor, the sliding mesh model is utilized.

B. Computational domain and simulation conditions

The computational domain, boundary conditions, and mesh details used for the simulation are shown in Fig. 2. The rotation zone is 1.2\( D \) in diameter and connected to the stationary zone measured 16\( D \) x 14\( D \) by sliding mesh method. The wind velocity \( U_0 = 7 \) m/s is applied to the inlet boundary, while the pressure condition is used at the outlet boundary. The turbulent quantities are specified in our previous research [11 - 13]. At the two-side boundaries, the symmetry condition is utilized. Besides, the rotor blades are applied no-slip condition. Table 2 displays various rotational speeds, denoted as \( \omega \), for each specific TSR. Note that for each rotor configuration, there is a different radius \( d \), the
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The table of values $\omega_1, \omega_2, \omega_3,$ and $\omega_4$ correspond to the values $d_1, d_2, d_3,$ and $d_4$ as shown in Fig. 1. The time step size is set to $2^\circ$/time step for one rotation.

The fine mesh is created in the interface between the rotor and the stator with a minimum mesh size of 0.005 and close to the blade with a minimum mesh size of 0.001. The coarse mesh is used for the stationary zone. The structured mesh was created near the blade with 20 layers of inflation, and the first layer of thickness is $10^{-5}$ mm (corresponding to mesh resolution of $y^+ < 1$), as shown in Fig. 2.

According to Table 3, the mesh independence is performed for the original configuration and A0 configuration at TSR = 0.8, including the coarse, medium, and fine mesh. In all cases, the difference in torque on the rotor between three meshes is less than 1% when increasing the number of mesh elements. Thus, the medium mesh is selected for the simulations in the next sections in light of this outcome.

### TABLE II. MESH INDEPENDENCE STUDY FOR THE ORIGINAL AND THE A0 ROTORS

<table>
<thead>
<tr>
<th></th>
<th>Original Moment [N.m]</th>
<th>Error [%] (Compared to Medium mesh)</th>
<th>A0</th>
<th>Moment [N.m]</th>
<th>Error [%] (Compared to Medium mesh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>4.286495</td>
<td>-0.095%</td>
<td>Coarse</td>
<td>4.28487</td>
<td>0.932%</td>
</tr>
<tr>
<td>Medium</td>
<td>4.290557</td>
<td></td>
<td>Medium</td>
<td>4.245307</td>
<td></td>
</tr>
<tr>
<td>Fine</td>
<td>4.321952</td>
<td>0.732%</td>
<td>Fine</td>
<td>4.278543</td>
<td>0.783%</td>
</tr>
</tbody>
</table>

Our previous studies examined time-step independence, variation, and turbulent model-sensitive [11].

### TABLE III. ROTATION SPEED OF ROTOR, $\omega$ [rad/s]

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>0.5</th>
<th>0.67</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
<th>1.1</th>
<th>1.2</th>
<th>1.3</th>
<th>1.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_1$</td>
<td>7</td>
<td>9.38</td>
<td>11.2</td>
<td>12.6</td>
<td>14</td>
<td>15.4</td>
<td>16.8</td>
<td>18.2</td>
<td>19.6</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>0.5</td>
<td>0.67</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
<td>1.1</td>
<td>1.2</td>
<td>1.3</td>
<td>1.4</td>
</tr>
<tr>
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<td>0.9</td>
<td>1.0</td>
<td>1.1</td>
<td>1.2</td>
<td>1.3</td>
<td>1.4</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>0.5</td>
<td>0.67</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
<td>1.1</td>
<td>1.2</td>
<td>1.3</td>
<td>1.4</td>
</tr>
</tbody>
</table>

### IV. RESULTS AND DISCUSSIONS

Fig. 3 compares power coefficients $C_p$ between the original configuration and rotor configurations with variable $\beta$ at different TSRs.

At rotor configurations A60 and A90, the power coefficient rapidly decreases to negative values as TSR gradually increases, so these two configurations are unusable during operation. Even with low TSR, the A90 produces poor performance.

Contrary to the above two configurations, the remaining configurations all create performance during operation. The A30 configuration gives slowly increasing performance up to TSR 1.2 until decreasing at higher speeds, while the A-30 gives gradually decreasing performance as TSR gradually increases. However, the disadvantage of these two configurations is that their resulting power coefficient is
lower than that of the original configuration. For the A0 configuration, performance is similar to the original configuration at low TSR < 0.8. However, it performs significantly better than other rotors at TSR > 0.8. The $C_p$ of the A0 configuration peaked at TSR 1.4, resulting in an efficiency improvement of up to 99.13% compared to the original configuration.

Fig. 3. Averaged $C_p$ between different rotor configurations

Fig. 4 shows the torque $T$ distribution in one rotation of the modified configurations with cut angle $\beta = -30^\circ$, 0°, and 30°, corresponding to configurations A-30, A0, and A30 in one rotation at TSR 1.0 and 1.4. According to TSR 1.0 graph, the A30 configuration produces the highest maximum value of moment coefficient compared to the other two. Specifically, this configuration’s maximum moment coefficient value reaches 1.03 at an angle position of 79°. However, the A30 configuration also has the smallest moment coefficient value of the three with a value of -0.77 at an angle of 174°. The same result can be observed in the TSR 1.4 graph. At both TSRs, the A0 configuration has the highest average value of moment coefficient, resulting in the highest power coefficient value of the three.

Fig. 4. Torque distribution in one rotation of rotor

Also in the 1.0 schematic, when comparing two configurations of A30 and A-30, it is shown that at the angle range from 24° to 113° and from 204° to 293°, the 30° configuration produces higher torque than the other. However, the opposite phenomenon is shown in the remaining angular ranges. Since the dominant moment regions of both configurations are relatively similar in magnitude, the corresponding power coefficient values do not have a large difference but that of the 30° one is slightly higher, as observed in Fig. 3. Furthermore, the A0 configuration produces a dominant moment area over A-30 configuration in most of the angular ranges. Although the A30 configuration produces more torque than the A0 configuration in the angular range from 34° to 108° and from 214° to 288°, this difference area is still smaller than the dominant region of the A0 configuration. As a result, the A0 configuration produces the best power coefficient value of all three configurations at TSR 1.0.

Moving to graph 1.4, the 0° configuration still has the best performance thanks to the ability to create a larger area of dominant moment than the other two configurations. Therefore, the power coefficient value of this configuration is still the largest of the three as shown in Fig. 3. It is worth noting here that there has been a change between the performance of the A30 and A-30 configurations. At TSR 1.4, the negative configuration produces higher torque than the positive one in a bigger angular range, and this dominant moment area is also larger. Hence, the power coefficient value of A-30 configuration is greater than that of the A30 configuration.

Fig. 5 and Fig. 6 depict the pressure distribution at 0° and 70° rotation angles of rotors configured with cut-off angles $\beta = -30^\circ$, 0°, and 30° at TSRs of 1.0 and 1.4, respectively. The advancing blade and the returning blade are denoted as (1) and (2).

Regarding TSR 1.0, at 0° rotation angle, low pressure areas appear on the concave sides and high pressure areas appear on the convex sides of all three rotors. These pressure differences enable the blades to produce torque. In particular,
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the tip low pressure region at advancing blade (1) of configuration A0 is observed to be larger in size than the other two configurations, resulting in the moment coefficient value of this rotor being also the highest among the three, as shown in Fig. 3. Meanwhile, in consideration of A30 configuration, the appearance of a significantly low pressure zone on the concave side and the transition of elliptical and circular blades of the advancing blade (1) has created an unfavorable moment and the moment coefficient value of A30 is the lowest. However, at the rotation angle of 70°, a large low-pressure region appears at the convex side of the advancing blade (1) of A30 configuration. This region has the largest area, followed by that of A0 and A-30, which made A30 the highest in moment coefficient.

![Fig. 5. Pressure contour around 3 rotors at rotation angle of 0° (left) and 70° (right) TSR 1.0](image)

Simlar phenomena can be observed in Fig. 6 at TSR 1.4. Owing to the adverse effects of low pressure zone at the concave side of the advancing blade (1), A30 configuration still produced the lowest value of moment coefficient at 0° rotation angle. Also at this angle, favorable pressure differences on blades contribute to the highest value of moment coefficient of A0 rotor. Additionally, at an angle 70°, a larger low pressure region on the convex surface of the advancing blade (1) on the A30 configuration is observed. This leads to the instantaneous moment at this corner position being the highest in all three configurations, as illustrated in Fig. 4.

![Fig. 6. Pressure contour around 3 rotors at rotation angle of 0° (left) and 70° (right) TSR 1.4](image)

To clarify the results analyzed in the previous figures, the two graphs in Fig. 7 illustrate the distribution of pressure on advancing (1) and returning (2) blades of three rotors A0, A30, and A-30 at 0° degree rotation angle of TSR 1.0. Strongly affected by the low pressure regions at the tip of advancing blades (1) as shown in Fig. 5, A0 and A30 configurations clearly have high differences in pressure at this position. Instead of that, A30 rotor appears to have a higher pressure disparity on the main of advancing blade due to the existence of an adversely low region of pressure on the concave side, which prevents it from producing favorable torque. In graph 2 in this figure, despite the higher pressure difference appearing at the tip of the returning blade (2) of A-30 configuration, the total pressure difference of this rotor is still lower than that of A0 configuration. For these reasons, the A0 rotor is proved to have the highest performance of the three.
In this study, multi-curve blade configurations that improve the performance of a Savonius rotor are numerically simulated. The advanced feature of the optimized design against the conventional one is analyzed through a sequence unsteady simulation using the commercial CFD software Ansys Fluent 2021R2. The length of the main blades is characterized by the cut angle parameter $\beta = -30^\circ$, $0^\circ$, $30^\circ$, $60^\circ$, and $90^\circ$. For configurations A60 and A90, the power coefficient rapidly decreases to negative values as TSR gradually increases. The remaining three configurations are shown to have higher performance at low TSRs from 0.1 to 0.9 but still lower than that of the original one. At TSRs higher than 0.9, A0 configuration produced more torque than the original, A30 and A-30 rotors, this peak power coefficient has been obtained by 99.13% at a tip speed ratio (TSR) of 1.4 when compared to Blackwell's experimental data of the original configuration. The result implies a high potential application of the rotor with A0 configuration for energy harvesting applications in wide wind conditions.

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