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Casing optimization of a Savonius wind turbine

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Abstract

In an attempt to enhance the performance of a Savonius Vertical Axis Wind Turbine (VAWT), case sizing optimization was performed utilizing Computational Fluid Dynamics (CFD) technique. A 2D parametric optimization process was employed to optimize a number of assigned design parameters of the casing's geometry. The configuration of El-Askary et al. (2015) was adopted as a starting baseline for the optimization. The turbine with the optimized casing provided a superior performance compared to a caseless one, specifically at low Tip Speed Ratios (TSRs). A maximum increase of 42.5% in the power coefficient (C_p) was attained at a tip speed ratio of 0.59. The obtained results demonstrate the nonexistence of a universal optimal casing shape that maintains peak turbine performance at all tip speed ratios. However, optimized casing dimensions follow a clear trend that is closely related to TSR values.

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Keywords: Savonius wind turbine; Optimization

1. Introduction

Drag-type Savonius Vertical Axis Wind Turbines (VAWTs) rely on the pressure difference on both sides of the blades for torque generation. These turbines are renowned for their excellent startup characteristics, ability to operate in omnidirectional wind flows, and ease of blade fabrication [1,2]. These unique characteristics are the motive behind the renewed interest in optimizing the performance of these devices. Researches have considered various design layouts to understand and improve the performance of a Savonius turbine. Kianifar, A. and Anbarsooz, M. [3] studied the effect of the Savonius blade curvature on the turbine's efficiency. It was concluded that having a rotor overlap resulted in an increase in the Power Coefficient (C_p) value up to a certain extent. Frikha et al. [4] conducted numerical investigations with experimental validations to characterize the performance of a multi-stage Savonius VAWT. Two to five stages were analyzed where it was shown that the Torque Coefficient (C_T) and power coefficient

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values increased with number of stages. Many more techniques have demonstrated their viability in improving the performance of Savonius VAWTs, one of which is the utilization of rotor's casing [5,6].

The goal of this study is to optimize the efficiency of a Savonius VAWT, with a radius of 0.08 m and an overlap ratio of 0.15, at different Tip Speed Ratios (TSRs). This is accomplished by parametrically optimizing the shape of a baseline rotor casing design, proposed by El-Askary et al. [7], which have shown superior performance compared to other published configurations. Different casing geometrical parameters are assigned and optimized following a proposed scheme. Computational Fluid Dynamics (CFD) technique is adopted utilizing the 2-equation SST $k - \omega$ turbulence model. Different optimal casing shapes are anticipated to be generated at different TSRs, hence a trend between the optimal casing shapes and TSR is thoroughly studied.

2. Methodology

The dimensions of the Savonius rotor is listed in Table 1. The geometry of the baseline casing design, suggested by El-Askary et al. [7], was parametrized to yield five distinctive optimization parameters shown in Fig. 1 (blue). Dimensions in red, like the distance between walls 1 and 3 ($5.7R$), were kept constant for a fair comparison between the generated samples.

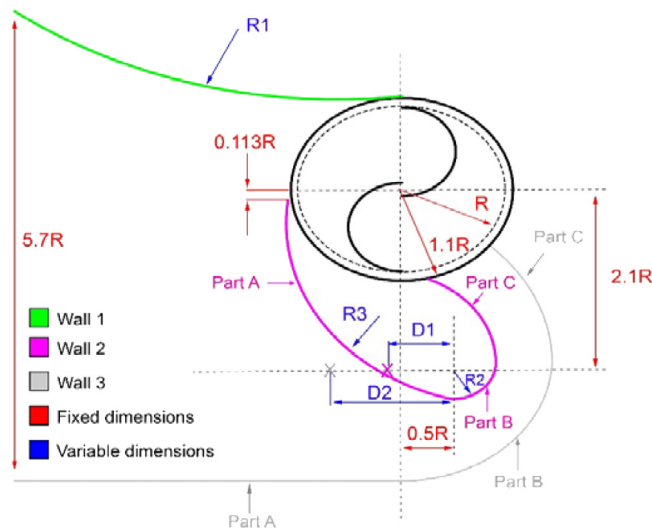


Fig. 1. Geometry of the Savonius turbine with casing, dimensions referred to in blue were varied during the optimization process. . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1. Dimensions of the Savonius rotor.

Blade radius	0.08 m
Rotor radius	0.149 m
Overlap ratio	0.15
Number of blades	2

At a given TSR, the optimization process started with radius R_1 , where different C_p values were generated for different values of R_1 . After observing a deteriorating trend in performance, the optimal value of R_1 was selected. With the optimized value of R_1 , the same process was followed with subsequent parameters R_2 , D_1 , R_3 , and finally D_2 , where the optimized value of a given parameter was adopted during the remaining process at a given TSR. Fig. 2 depicts the order of the optimization process, highlighting also the effect on the casing's geometry resulting from selecting different values for the geometrical parameters.

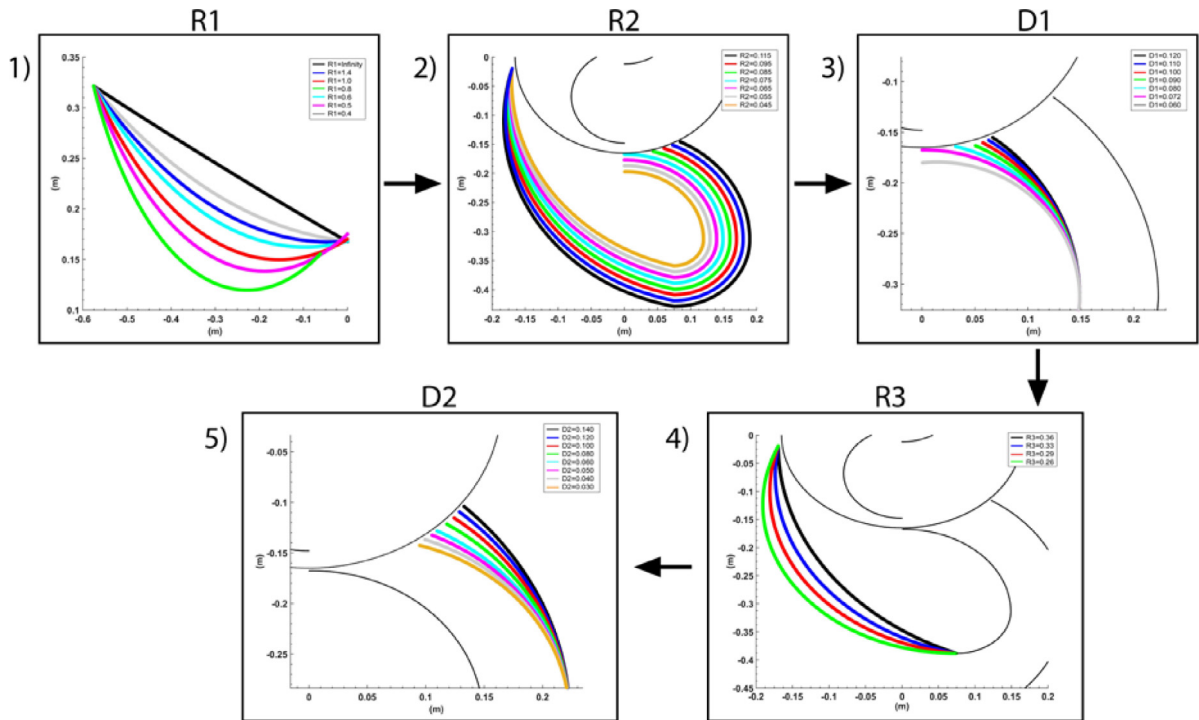


Fig. 2. The optimization order of the different casing geometrical parameters.

3. Numerical setup

The governing transient 2D flow equations were solved using ANSYS Fluent. The SST $k - \omega$ turbulence model was adopted in the present simulations owing to its accuracy and acceptable computational demands. The computational domain was divided into two flow zones, rotor and wind tunnel, with a sliding interface. The domain dimensions exceeded the minimum sizing guidelines published by Rezaeiha et al. [8], which assured the omission of blockage effects and the full development of the wake region. The generated mesh was composed of unstructured triangular elements with inflation layers near solid surfaces in order to ensure that $y^+ \leq 1.0$. Appropriate mesh controls were deployed in order to refine the mesh in certain areas where information was expected to vary rapidly. Initial studies were conducted in order to generate a mesh-independent grid, and select the right time step size. Consequently, these calculations showed that a grid with 332,768 elements and a time step size equivalent to 1° rotor rotation had to be utilized. The utilized boundary conditions are delineated in Table 2.

Table 2. Boundary conditions used in the numerical analyses.

Free stream velocity (U)	6 m/s
Turbulence intensity (I)	5%
Outlet gauge pressure	0 Pa
Blade and casing walls	Non-slip
Upper and lower domain bounds	Symmetry

4. Results

Different power coefficient curves for different turbine configurations are shown in Fig. 3 (left), including relevant experimental data (blue) published by Fujisawa [9]. The optimized C_p values (green) were generated following the optimization scheme described previously with more than 100 numerical simulations conducted involving different casing shapes and TSRs. It is evident that the performance of the turbine with the optimized casing is substantially improved compared to a caseless configuration, where C_p increases by 21%, 27%, and 15% at TSRs 0.59, 0.76, and

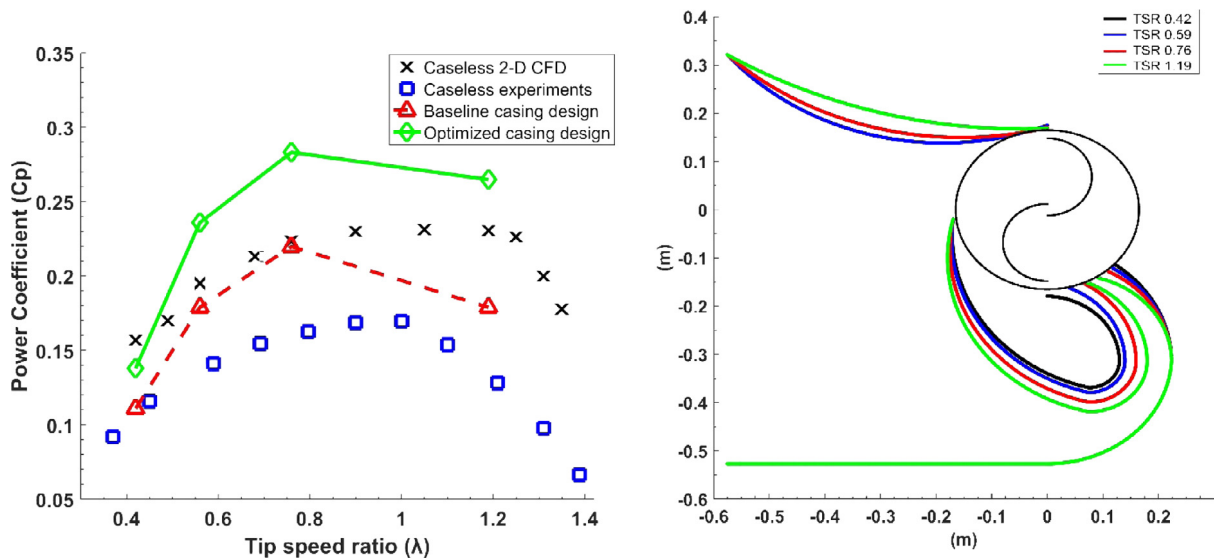


Fig. 3. Power coefficient values from 2D simulations (left), and the generated optimized casing shapes at different TSRs (right). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1.19 respectively. At $TSR = 0.42$, the performance of the optimized casing slightly drops with $C_p = 0.14$. Relative to the baseline casing design, the value of C_p is increased by 24%, 32%, 29%, and 48% at $TSRs$ of 0.42, 0.59, 0.76, and 1.19, respectively. Fig. 3 (right), shows the resulting optimized casing shapes which are clearly different at various $TSRs$ as anticipated. A trend in the casing's geometry and TSR can be readily pointed out, where with increasing TSR : curvature of wall 1 decreases, distance between walls 2 and 3 decreases, and returning blade jet angle decreases. The last two coherent observations signal that there is certain value of the returning blade angle of attack that should be maintained for optimal performance. Inspecting the C_p values of the caseless configuration, it is evident that 2D CFD overestimates the performance of the turbine, since the generated C_p curve from 2D CFD is shifted vertically upwards relative to the experimental data. This shift effect is frequently reported in published 2D studies [10], and is a consequence of following a rather computationally feasible approach. Following a similar cumbersome optimization process on a 3D model would, for sure, require substantial computational resources, as shown by Antar and Elkhoury [11].

Torque coefficient curves at $TSR = 0.76$ is shown in Fig. 4, where it is clear that the torque generated by the turbine is considerably amplified. The maximum value of C_T increases by almost three times relative to the caseless configuration, and the optimized C_T never attains a negative value. In order to further investigate the issue, instantaneous pressure contours for the caseless, baseline, and optimized configurations with C_T equal to 0.36, 0.72, and 1.16 respectively, are considered at $TSR = 0.76$ and $\theta = 145^\circ$ (Fig. 5). It can be seen that the positive pressure area on the concave side of the advancing blade is the greatest for the optimized configuration, followed by the baseline configuration and finally the caseless one. The same description applies for the negative pressure area on the convex side of the blade, which is the greatest for the optimized design. This increase in negative pressure is a consequence of the nozzle-like effect resulting from having a curved wall 1, which is not presented in the baseline design or the caseless configuration. Consequently, the pressure difference on the advancing blade is tremendously increased, and is responsible for the elevated C_T value. This outweighs the increase in pressure difference on the returning blade, which generates counter-rotating torque (Fig. 5).

5. Conclusion

The geometry of a casing that engulfed the rotor of a Savonius turbine was successfully optimized for maximum efficiency at four $TSRs$. Below are the main findings from the conducted parametric CFD investigations:

- Compared to a caseless Savonius turbine, C_p increased by 21%, 27%, and 15% at $TSRs$ 0.59, 0.76, and 1.19 respectively when adopting the optimized casing designs. C_p marginally drop to 0.14 at TSR 0.42.

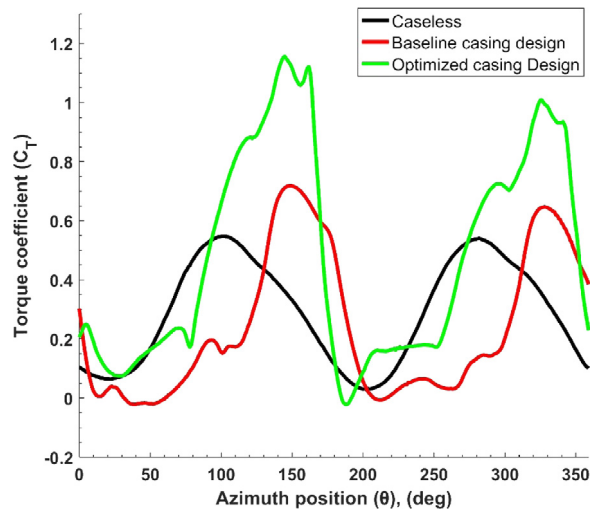


Fig. 4. Torque coefficient curves from numerical simulations at $TSR = 0.76$.

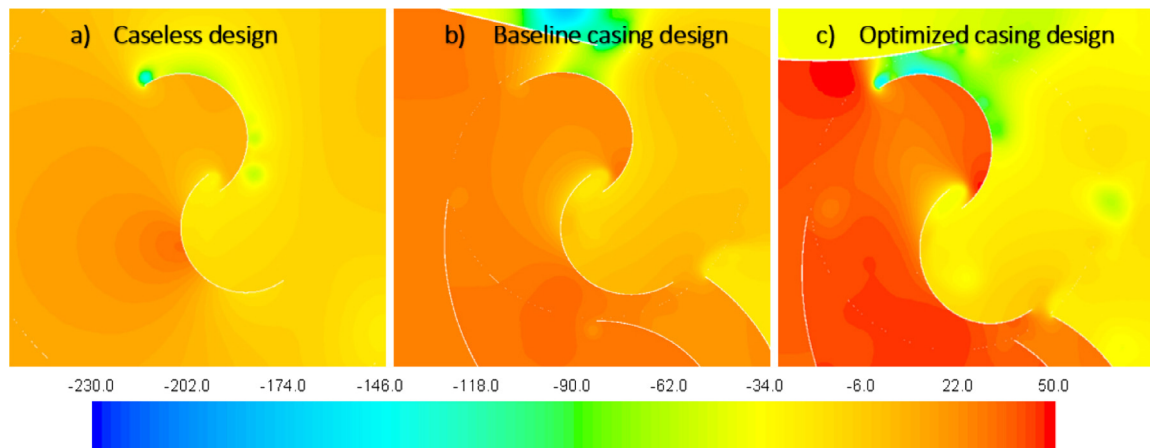


Fig. 5. Instantaneous pressure (Pa) contours at $TSR = 0.76$ and $\theta = 145^\circ$.

- Relative to the baseline casing design, C_p increased by 24%, 32%, 29%, and 48% at TSRs of 0.42, 0.59, 0.76, and 1.19 respectively when utilizing the optimized casing designs.
- The dimensions of the optimized casing had a clear trend with TSR, whereby with increasing TSR: The curvature of wall 1 decreased, the distance between walls 2 and 3 decreased, and the returning blade jet angle decreased.
- 2D Reynolds-Averaged Navier–Stokes simulations seem to be unable to replicate the complicated flow around a Savonius VAWT. Hence, performing 3D numerical simulations relying on hybrid resolving-modeling techniques like Detached Eddy Simulations (DES) or Partially Averaged Navier–Stokes (PANS) render the simulation more accurate.

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