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Blade shape optimization of the Savonius wind turbine using a genetic algorithm

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HIGHLIGHTS

- GA is incorporated into CFD for the optimization of Savonius wind turbine's blades.
- 33% improvement in power coefficient is observed for turbine with optimal blades.
- Turbine with optimal blades outperforms conventional one at a wide range of TSR.

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ABSTRACT

The Savonius wind turbine is one of the best candidates for harvesting wind energy in an urban environment, due to unique features such as compactness, simple assembly, low noise level, self-starting ability at low wind speed, and low cost. However, the conventional Savonius wind turbine with semicircular blades has a relatively low power coefficient. This work focuses on optimizing the shape of the blade of the Savonius wind turbine to further improve its power coefficient. An evolutionary-based genetic algorithm (GA) is incorporated into computational fluid dynamics (CFD) simulations, thereby coupling blade geometry definition with mesh generation and fitness function evaluation in an iterative process. Three variable points along the blade cross-section are used to define the geometry of the blade arc, and the objective function of GA is set to maximize the power coefficient. Two-dimensional flow around the wind turbine is modeled by the shear-stress transport (SST) k-ω turbulence model and solved through the finite-volume method in ANSYS Fluent. Three GA optimization runs with different population and genetic operations have been carried out to provide the optimal shape of the blade of the Savonius turbine. Compared to the wind turbine with semicircular blades, the wind turbine with optimal blades and a tip speed ratio (*TSR*) of 0.8 achieved significant improvement (up to 33%) on the time-averaged power coefficient. In addition, the Savonius turbine with optimal blades outperformed the one with semicircular blades at a wide range of *TSR* (= 0.6–1.2), suggesting that the Savonius wind turbine with optimal blades has great potential to be applied in the real urban environment. The aerodynamic forces and flow structures pertaining to both wind turbines with optimal and semicircular blades are compared and discussed, to improve our understanding on their underlying mechanisms and to further improve their performance.

1. Introduction

Wind energy is an abundant, clean resource that greatly reduces the economic, social and environmental impact from energy consumption. So far, wind energy has mostly been harvested in such open environment as a suburban or offshore area, using large-scale propeller-type horizontal-axis wind turbines (HAWTs) [1]. There is no extensive utilization of wind energy in high-density high-rise urban environments [2]. Due to its unique features such as compactness, simple assembly, omni-directionality, low noise level, self-starting ability at low wind speed, and low cost, the Savonius wind turbine or rotor, one type of vertical-axis wind turbines (VAWTs), serves as one of the wind power converters for distributed small-scale energy harvesting systems in urban environments [3]. Yet, the performance of the conventional Savonius turbine with two straight semicircular blades, in terms of power coefficient (C_p), is relatively low and requires further improvement.

The performance of the conventional Savonius wind turbine can be improved using defectors or curtains [4–7]. These deflectors are basically designed to simultaneously gather the oncoming wind for the advancing blade and direct the oncoming wind away from the returning blade. Mohamed et al. [7] placed a flat plate upstream of the returning blade and optimized its position and orientation based on evolutionary

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Table 1
Recent work on the blade shape optimization for the Savonius turbine.

Investigation	Blade shape	$\overline{C}_p$ improvement	Remarks
Kamoji et al. [8]	Bach type	10.5%	Wind tunnel test
Mohamed et al. [9]	Optimized shape using Genetic Algorithm	38.9% (with a pre-installed deflector)	Numerical simulation
Kacprzak et al. [10]	Semi-elliptic type	10.3%	Numerical simulation
	Bach type	16.1%	
Driss et al. [11]	Various bucket arc angles	–	Both numerical simulation and wind tunnel test
Tartuferi et al. [12]	SR3345 Airfoil	10% at TSR < 0.5	Numerical simulation
	SR5050 Airfoil	Improvement only at TSR > 0.9	
Roy and Saha [13]	Semi-elliptic type	13.0%	Wind tunnel test
	Benesh type	26.1%	
	Modified Bach type	30.4%	
	Newly developed (Similar to Bach type)	34.8%	
Roy and Ducoin [14]	Newly developed (Similar to Bach type)	32.1%	Numerical simulation
Yang et al. [15]	Deflectable arc blade	41.1%	Wind tunnel test and numerical simulation
Kumar & Saini [16]	Twisted blade	10%	Numerical simulation
Tian et al. [17]	Optimized convex and concave sides of the blade using particle swarm optimization	4.41%	Numerical simulation

algorithms. A considerable improvement of > 27% in the time-averaged power coefficient ($\overline{C}_p$) was achieved for the turbine with the plate deflector optimally-positioned, compared with that without a deflector. Experimental validation of this technique was conducted by Golecha et al. [6]. Altan & Atılgan [4] deployed two straight plates upstream of the Savonius turbine; as such, a convergent channel was formed to gather the oncoming wind. This design was further developed by El-Askary et al. [5], that is, one part of the oncoming wind was guided through a smooth channel toward the inner side of the returning blade, resulting in an enhanced negative pressure therein. A significant improvement was made, i.e., the maximum power coefficient was increased to $\overline{C}_p = 0.52$ at $TSR \leq 0.82$. Nevertheless, these deflectors introduce a highly turbulent wake and make the turbine system complex and direction-dependent [5].

Changing the shape of the Savonius turbine's blades can improve its performance. Previous investigations are summarized in Table 1. Different types of blades have been used in the literature, such as the Bach type, Benesh type, semi-elliptic type, and airfoils. Kamoji et al. [8] and Kacprzak et al. [10] adopted the Bach-type blades for the Savonius turbine and studied the effects of geometrical parameters on the performance. Their wind tunnel and numerical simulations indicated that $\overline{C}_p$ was increased by up to 16% for the modified Savonius turbine given the optimal geometrical parameters, compared with that of the conventional turbine with semicircular blades. The semi-elliptic blades studied by Kacprzak et al. [10], achieved a considerable improvement of about 10% in $\overline{C}_p$. Recently, based on the Bach-type blade, 13–14 made further modification to the blade shape and obtained a significant increase in $\overline{C}_p$ by up to 35%. Regarding the blades with variant thickness, Tartuferi et al. [12] used different types of airfoils as the turbine blades. Their numerical simulations indicated that $\overline{C}_p$ was improved by 10% for the SR3345 airfoil blade at a low TSR (< 0.5), compared with that of the semicircular blades. Aerodynamic forces and flow structures associated with the modified blades were examined in detail, with a comparison to that of the semicircular blades. Kacprzak et al. [10] and Roy and Ducoin [14] presented the force coefficients, pressure and velocity distributions for the developed blades. Roy and Ducoin [14] ascribed the enhanced performance of the turbine to the increased lift force and elongated momentum arms. Effects of the blade arc angle on the turbulent wake were conducted by Driss et al. [11], though without $\overline{C}_p$ improvement reported. Recently, Yang et al. [15] designed a turbine system with four deflectable arc blades, whose incident angle relative to the oncoming wind can be changed during rotation. The torque acting on the advancing blades was greatly increased while drag on the returning blades was greatly reduced, thus resulting in a significant improvement, up to 41.1%, in the maximum power coefficient. The performance of the Savonius turbine with two twisted blades was investigated by Kumar and Saini [16], based on a systematic procedure combining variable parameters setting, blade model generation and CFD simulation. A considerable improvement in $\overline{C}_p$, about 10%, was achieved. Nevertheless, the aforementioned efforts mostly modified the shape of the turbine's blades using trial-and-error; no advanced numerical optimization algorithms or approaches are involved.

Although advanced numerical optimization approaches such as neuro-fuzzy (e.g., [18,19]) have been applied to the optimization of other types of wind turbine systems [20], only a few studies have focused on modifying the shape of the Savonius turbine's blades using numerical optimization algorithms. Using evolutionary-based genetic algorithm (GA), Mohamed et al. [9] attempted to optimize the blade skeleton for the Savonius wind turbine. The Savonius turbine with optimal blades achieved a great improvement in $\overline{C}_p$, about 39%, over the turbine with semicircular blades. However, a flat plate deflector was pre-installed upstream of the returning blade, rendering the turbine system complex and direction-dependent. Also, the shape of the blade could be different in the absence of the pre-installed deflector. A particle swarm optimization algorithm based on a response surface model was applied by Tian et al. [17] in optimizing the convex and concave surfaces of the blade for the Savonius turbine. The shape of the blade surfaces was constrained by a semi-ellipse and the length of the short-axis was the only variable in their optimization. Improvement in $\overline{C}_p$ was about 4.4% for the Savonius turbine with optimal blades.

The present work aims to apply the evolutionary-based GA in the optimization of the blade shape for the Savonius wind turbine working in a free stream. CFD simulations are incorporated into the procedure of GA optimization. Furthermore, the performance of the Savonius turbine with optimal blades is investigated at a wide range of tip speed ratio (TSR) to examine the feasibility of applying it in real-life applications. This work also aims to present the flow physics underlying the behaviour of the optimal blades, based on detailed numerical simulations, in order to improve our understanding of the aerodynamics of the Savonius turbine. The paper is organized as follows. Section 2 introduces briefly GA, followed by the description of GA-based optimization in Section 3. The numerical simulation aspects are given in Section 4. Results are presented and discussed in Section 5. Conclusions and remarks are given in Section 6.

2. Genetic algorithm

Genetic algorithms (GAs) are stochastic search algorithms inspired from biological evolution and based on the Darwin's theory of the survival of the fittest [21]. As such, GAs present an intelligent approach