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Performance characteristics of a horizontal axis turbine with fusion winglet

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ABSTRACT

Any technique or method that can improve the efficiency in exploiting renewable wind or marine current energy has got a great significance today. It has been reported that adding a winglet at the tip of the rotor blades on a horizontal axis wind turbine can increase its power performance. The purpose of this paper is to adopt a numerical method to investigate the effects of different winglet configurations on turbine performance, especially focusing on the direction for the winglet tip to point towards (the suction side, pressure side or both sides of the main blade). The results show that the new design of an integrated fusion winglet proposed in this paper can generally improve the main blade's power producing ability, which is further enhanced with the increase of turbine's tip speed ratio with a maximum power augmentation of about 3.96%. No matter which direction the winglet tip faces, the installation angle of the winglet should match well with the real angle of incoming flow. As a whole, the turbine with winglet of two tips facing to both sides of the main blade can produce much more power than the one of winglet configuration whose tip faces only one side for different blade hub pitch angles and vast majority of tip speed ratios. The working principle behind the winglet in improving turbine performance may be that it can block the downwash fluid easily flowing around the tip section of the main blade from the pressure side to suction side, and hence diffuse and spread out the tip vortex. As a result, it finally decreases the energy loss. Besides, the relative projected rotor area in incoming flow direction will also be reduced due to the addition of the winglet, which is also helpful to turbine's power coefficient.

1. Introduction

In recent years, the exploitation of renewable wind or marine current energy has attracted strong scientific interest and experienced rapid development [1]. As a horizontal axis turbine is the most common design that converts kinetic energy of a moving fluid into electrical power, it is of great importance to improve the turbine energy extraction efficiency.

The blade of a horizontal axis turbine is similar with the wing of airplane or glider. A lot of practice has proved that the stationary plane wing with an added winglet can inhibit tip vortex, and hence reduce the induced drag, leading to a higher lift-to-drag ratio of the wing and enhance the working stability [2]. When a winglet is integrated to a rotating horizontal axis turbine blade, whether it will still be effective in reducing the energy loss of the main blade to improve the energy absorption performance of the turbine? Some preliminary researches on this topic were carried out with the aid of numerical or experimental investigations.

A tip vane turbine was first used in a wind energy concentrator system and its positive effect on power increment was proved based on wind tunnel test [3].

A maximum power augmentation of about 14.5% for a horizontal axis wind turbine was experimentally achieved for the rotors with smaller aspect ratios at lower wind speeds due to a Mie-type vane application [4].

According to the computational results obtained by using a developed free wake lifting line code and verified by Computational Fluid Dynamics (CFD) solver, Gaunaa, Johansen and Sørensen [5–7] argued that the power improvement obtainable with winglets is due to a reduction of tip effects, and is however not caused by the downwind vortex shift due to winglets, which has been widely accepted in this research area. Their CFD results show that adding a winglet to an already aerodynamically optimized rotor design

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Nomenclature

A	rotor area (m^2)
CP	power coefficient ($T\omega/(0.5\rho U^3 A)$)
CT	thrust coefficient ($F/(0.5\rho U^2 A)$)
D	rotor diameter (m)
F	rotor thrust (N)
R	blade tip radius (m)
T	rotor torque (N m)
TSR	tip speed ratio ($\omega R/U$)
U	flow speed (m/s)
ρ	fluid density (kg/m^3)
ω	rotational speed of rotor (rad/s)

increases generated power of up to 2.2%. The additional increase in thrust is up to 3.9%. When changing the operational conditions slightly, the effects are still favorable.

Gupta and Amano [8] carried out a parameter study focusing on the key winglet parameters of cant angle and winglet height. If winglet is bent towards the pressure (upstream) side, the results show that adding a winglet to a straight blade increases its power output by 2%–20%. In addition, winglet which has a cant angle of 45° performs better. Also, the power generation increases with the increase of the winglet height.

Aravindkumar's [9] experimental results showed that the power output of a small wind turbine generator whose blades are equipped with winglets is increased by 2.01% and its noise level is reduced by 25%, compared with the wind turbine blades without winglets. Zhang's [10] studies also obtained the similar results.

The effects of changing the blade winglet configuration including the winglet height and curvature radius on the power performance of small wind turbine rotor models were investigated experimentally [11]. It is recommended that adding a winglet with a smaller curvature radius and sufficient height to the wind turbine rotor blades can capture the wind's energy much more efficiently than a rotor without winglets in lower wind speed regions.

To investigate the winglet effect on the power production for a wind turbine blade, the aerodynamic performance-based design and optimization were conducted with the help of computational fluid dynamics (CFD) and artificial neural network. In the winglet design, the variable parameters used were the cant and twist angles of the winglet and the objective function of the optimizer was to maximize the torque about the axis of rotation. Multipoint optimization was carried out for three different operating wind speeds. The final optimized winglet showed around 9% increase in the power production [12].

The aerodynamic characteristics of a single stationary blade with different blade tip configurations were experimentally investigated. Results indicated that the lift-to-drag ratio of the blade with the upwind winglet was increased by around 26% compared to a straight blade without winglet, whereas the downwind winglet resulted in about 27% reduction in the lift-to-drag ratio [13].

The effects of downstream-facing winglets on the wake dynamics and performance of a model wind turbine were experimentally studied [14]. Results show an increase in the power and thrust coefficients of 8.2% and 15.0% for the winglet case. The higher thrust coefficient created a region of enhanced mean shear and turbulence in the outer portion of the wake. The winglets did not significantly change the tip-vortex strength, but higher levels of turbulence in the far wake decreased the tip-vortex strength.

Furthermore, researchers have carried out some numerical and experimental works to investigate the effects of winglet applied to a horizontal axis turbine. These published studies proved that the addition of winglet to the tip of the rotating blade can improve the turbine's performance to a certain extent. However, the disagreement on the understanding of the working mechanism is still existing at present, and the studies on performance variation with changing winglet's main design parameters are not deep enough. In particular, there is very little discussion or recognition of the problem of the optimal direction for the tip of the winglet to face which side of the turbine blade (the pressure side, suction side or both sides).

Therefore, the main purposes of this article are to investigate the effects of different winglet configurations on the turbine performance with the aid of numerical methods, analyze the working principle behind the winglet in the rotating case, and outline the types of turbine performance improvements that operators can expect from the application of winglet.

2. Computational methodology and model validation

In this section, the chosen physical model and related test data, computational region and its discretization, applied numerical methodology and boundary conditions, sensitivity study and model validation are introduced in detail.

2.1. Physical model and tests

The chosen physical model of a horizontal axis marine current turbine simulated in this paper was designed by the research group lead by A. S. Bahaj [15] at the University of Southampton. The rotor radius is 400 mm with a hub radius of 50 mm, and the number of blade is three. The blade profiles shape was developed bases on the widely used airfoil series NACA 63-8xx, and the applied geometric airfoil parameters were shown in Table 1.

A prototype turbine was manufactured and thoroughly tested in a cavitation tunnel (at QinetiQ, Haslar, Gosport, with working section particulars of 5 m length, 2.4 m breadth, 1.2 m height and 8 m/s max flow speed) and a towing tank (at Southampton Institute, with working section particulars of 60 m length, 3.7 m breadth, 1.8 m depth and 4.5 m/s max carriage speed), respectively, for the purpose of comparison. In order to present the results for free stream conditions, the experimental results of turbine power coefficient (CP) and thrust coefficient (CT) have been corrected for tunnel blockage effect and was openly published. As their experiments

Table 1
Detailed geometry information of turbine blade [15].

r/R	Radius(mm)	c/R	Pitch distribution(deg)	t/c (%)
0.2	80	0.125	15	24
0.25	100	0.1203	12.1	22.5
0.3	120	0.1156	9.5	20.7
0.35	140	0.1109	7.6	19.5
0.4	160	0.1063	6.1	18.7
0.45	180	0.1016	4.9	18.1
0.5	200	0.0969	3.9	17.6
0.55	220	0.0922	3.1	17.1
0.6	240	0.0875	2.4	16.6
0.65	260	0.0828	1.9	16.1
0.7	280	0.0781	1.5	15.6
0.75	300	0.0734	1.2	15.1
0.8	320	0.0688	0.9	14.6
0.85	340	0.0641	0.6	14.1
0.9	360	0.0594	0.4	13.6
0.95	380	0.0547	0.2	13.1
1	400	0.05	0	12.6