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Numerical prediction for the aerodynamic performance of Turbosail type wind turbine using a vortex model

Cherif Hcini [a,*], Essia Abidi [a], Badreddine Kamoun [a], David Afungchui [b]

[a] Laboratory of Applied Physics, Faculty of Sciences of Sfax, Department of Physics, Road Soukra: Km 4, BP n° 802, Sfax 3038, Tunisia
[b] University of Bamenda, Faculty of Sciences, Department of Physics, P.O. Box 39, Bambili, Cameroon

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A B S T R A C T

One of attracting concepts has been the use of Turbosail principle to produce lift from aspirated cylinders with flap in various engineering applications. The Emerging of the Turbosail principle in wind turbine technology is promising to develop and to design innovative devices. The objective of this project paper is to develop an efficient numerical code, for the prediction of the aerodynamic characteristics of Turbosail type wind turbine with very thick aspirated profiles. A vortex model has been treated based on the lifting line theory. The results predicted by the code developed, have been compared and validated by some numerical and experimental data.

1. Introduction

Growing Impacts of Global Warming and pollution forced many nations to renewable energy sources. However, due to the rapidly increasing population and the industrial production, the clean energy should be obtained efficiently. Prominent among those renewable energy sources is wind energy which is widely available at a competitive cost [1].

The power extracted from wind energy is obtained through using many devices. One of the most efficient concepts has been the use of Turbosail principle, derived from a principle known as the Magnus Effect [2,3] to produce lift from thick sucked airfoil in various engineering applications. The Turbosail is made essentially of an ovoid-section cylinder with longitudinal suction zones and a thin movable flap on the lower side of the trailing edge [4,5]. Fig. 1 shows a perspective view of the Turbosail model and Fig. 2 is the view in the median plane. The first successful device based on the principle of Turbosail goes back to 1980, when the foundation Cousteau has manufactured the first ship operating with Magnus force using a large aspirated cylinder to propel his ship Alcyone [6].

Researches on the Turbosail model have mostly been geared towards experimental studies. Few devices using this principle were operated successfully. Wind-tunnel studies on the Turbosail have been carried out by Charrier et al. [6]. Experimental results of the lift, the drag and the pressure distribution have been presented for a Turbosail with a forward elliptic profile. Shiii et al. [7,8] and Low et al. [9] have tested a wind-assisted ship propulsion device (WASP), consisting of a cylinder-flap wing with boundary layer suction in order to improve its performances. Cousteau et al. [4] mentioned that this system can be used to constitute the blade of horizontal axis wind turbine. But until today, the most patents on Turbosail principle were published in the areas of naval applications. To have an optimal blade of wind turbine, the coefficient of circulation must be quasi-constant along the span, which leads either to important chords on the side of the root or to higher coefficients of lift, that just cannot be provided by the classical profiles. The adaptation of the profile type Turbosail in the case of a wind turbine blade could allow obtaining this quasi-constant circulation. In this regard, the only experimental study is assigned to Lemaigre et al. [10], which have designed and prototyped a wind turbine with thick sucked airfoils type Turbosail: A windmill of approximately 2 m diameter with 4 blades. Each blade is provided with an aspirated part on 45% of its span, whose the profile is an elliptical careened cylinder with a maximum thickness of 67% and a flap deflection of 40°. The suction is carried out by centrifugation of the aspirated air which is rejected at the tip of the blade. Its location is on the upper side between 100° and 135° from the chord line (in the clockwise direction). The other part of the blade is constituted

* Corresponding author.
E-mail address: hcinicherif@hotmail.com (C. Hcini).

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Nomenclature

R	radius of the rotor disc
y	radial coordinate along the span of the blade
$l(y)$	chord of a blade section at the radius y
$c(y)$	reduced chord of a blade section at the radius y
Np	number of blades of the wind turbine
k	half the slope of the lift curve from the Kutta –Joukowsky theorem
V_∞	free stream wind velocity
W_1	relative velocity of the wind
w_a	axial component of the induced velocity
w_t	tangential component of the induced velocity
u_i	reduced axial induced velocity
v_i	reduced tangential induced velocity
W^*	average effective velocity of wind along the aspirated part of the blade
Γ	circulation along the blade
C_Γ	circulation coefficient
C_l	lift coefficient
C_d	drag coefficient
C_p	power coefficient
C_T	thrust coefficient
C_q	torque coefficient
ζ	reduced radius of the rotor disc
$\chi = (1/\lambda)$	tip speed ratio
λ_0	parameter characterizing the real advance pitch of the vortex system.
Ω	rotational velocity of the wind turbine
α	angle of attack
β	aerodynamic pitch angle
ϕ	induced angle
Θ	pitch angle with respect to the axis of zero incidence
i	inductor point
j	inductor point

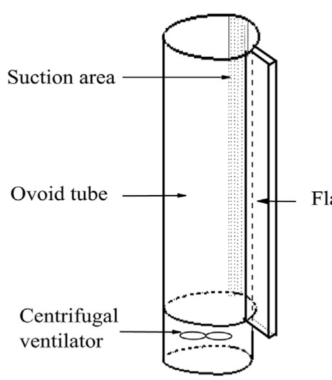

Fig. 1. Perspective view of the Turbosail.

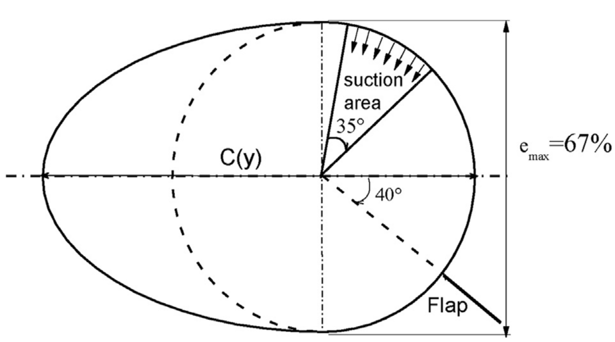

Fig. 2. Turbosail airfoil.

by NACA 4424 airfoils following a trapezoidal variation of the chord (see Fig. 3).

The rotor has efficiency nearly as good as the best three-blade turbine and sharply higher than the other classical types of wind turbines such as multi blade or the Darrieus turbine. The advantage of this device is the simplicity in conception and easy to manufacture [10].

Despite their practical interest, there are few computational studies available in the literature concerning the study of the aerodynamic characteristics of this wind turbine with airfoil type

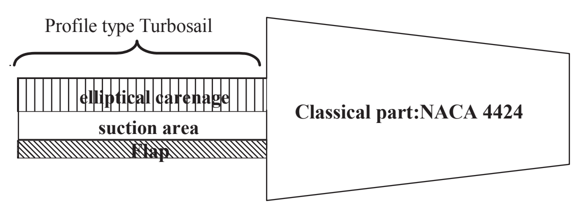

Fig. 3. Form of the blade of the studied wind turbine.

Turbosail. The only fundamental theoretical study on this type of wind turbine documented in literature is attributed to Lemaigre [10]. He has performed numerical simulations based on the blade element method to predict its aerodynamic performances. The blade element method (BEM) is well documented in literature while the reader is referred to the relevant references relative to the theory [11–17].

The purpose of this study is to develop an analysis tool based on lifting-vortex line theory for predicting numerically the aerodynamic performances of the wind turbine blade type Turbosail. Compared with the BEM method, the vortex theory is able to offer more physical solutions for attached flow conditions; it is also valid over a wide range of turbine operating conditions [18]. The method was formulated by Goldstein [19] and Lock [20]. Each blade surface is assumed to a lifting line and sheds a helicoidal sheet of vorticity filaments originating from the trailing edge [19,21,22]. The viscous corrections are made by using 2D viscous data for the section lift and drag. The circulation distribution along the blade is obtained by introducing an arbitrary law of axial induced velocities which is derived from the approximation of Morgan and Wrench [23,24]. Then, we can also calculate practical component of induced velocity, thrust, torque, and power coefficient. The problem is solved using an iterative procedure. Some of the predictions of the code developed are presented and validated by the experimental data of foundation Cousteau [10] and the numerical result of Lemaigre [10].

2. Mathematical model

Based on the vortex theory, the blade span-length R is discretized into number of points indexed by j of elementary spacing $\Delta\zeta$ [25]. Each discretization point represents a helical vortices