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Numerical optimization of the asymmetric blades mounted on a vertical axis cross-flow wind turbine☆

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ABSTRACT

In this paper, response surface methodology (RSM) based on central composite design (CCD) is applied to obtain an optimization design for the asymmetric blades geometry of a vertical axis wind turbine (VAWT). Turbine's airfoils are simulated by using computational fluid dynamics (CFD). The SST K-ω model is used to simulate turbulent flow around the asymmetric blade. The free-stream velocity is constant and the rotation speed of turbine rotor is considered 350 to 600 rpm. Results show that the maximum torque coefficient is obtained at rotation of 450 rpm.

1. Introduction

Although considerable progress in wind energy has already been achieved, the present technical design relying exclusively on horizontal axis turbines is not yet adequate to develop reliable wind energy converters, particularly for conditions corresponding to low wind speeds and/or urban areas. Vertical axis wind turbines (VAWT) like the Darrieus turbine appears to be particularly promising for such conditions. VAWTs can operate with any wind direction and are a recent option for urban installations; their rotor is characterized by an inherently unsteady behavior due to the continuous variation of the angle of attack during blade rotations. The unsteady flow of rotors spinning about an axis normal to the plane of the incoming flow (helicopter blades are the most familiar example) has a significant impact on the overall performance of the machine. Mohamed [1] categorized the advantages and disadvantages of VAWTs as follows:

I. Disadvantages:
- Low efficiency;
- Difficulties by self-starting;
- Resonance issues and material fatigue due to oscillating power output;
- Much larger shaft bending momentum due to substantially larger bearing and shaft loads.

II. Advantages:
- A greater compactness;
- A simpler design, leading to relatively low costs;
- The possibility of housing sensitive mechanical and electrical components, gearbox and generator at ground level;
- The absence of any yaw-control system.

Also, Wilks [2] pointed out that vertical turbines have lower sound noise compared to horizontal cases as an advantage for VAWT. Based on the above advantages, Peace [3] realized that wind energy in the future will be completely dependent to vertical axis turbines with grater surfaces and output power. So, many researchers attempt to improve the VAWT performance by experimental or numerical modeling. For instance, Trivellato et al. [4] investigated the Courante Friedrichs Lewy (CFL) criterion for the stability of numerical schemes at the conservative interface that divides rotating grids embedded within fixed grids for blades of a VAWT. Castelli et al. [5] presented a CFD model for the evaluation of energy performance and aerodynamics allowing the correlation between flow geometric characteristics (such as blade angles of attack) and dynamic quantities (such as rotor torque and blade tangential and normal forces). They concluded that applied model is a powerful design and optimization tool for the development of new rotor architectures for which test data is not available. Also, a 2D CFD model was calibrated and validated comparing the numerical results with two different types of H-Darrieus experimental data by Lanzafame et al. [6]. In an experimental study, Howell et al. [7] investigated the effect of roughness, smoothness and number of blades on a special design of a cross flow vertical axis turbine. Recently, Bedon et al. [8]

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reported a relevant increase in performance achieved for the results of optimization of VAWT and showed that the numerical optimization can be successfully adopted in vertical-axis wind turbine design procedures. Another multi-objective optimization using genetic algorithm is utilized by Mortazavi et al. [9] to obtain a Pareto optimal set of solutions for geometrical characteristics of airfoil sections for 10-meter blades of a horizontal axis wind turbine. Siddiquie et al. [10] investigated the geometry effect on the performance of a VAWT and concluded that that two-dimensional approximation can over predict the performance by 32% and a similar trend was also observed for other geometric and flow approximations.

Response surface methodology (RSM) is a collection of mathematical and statistical techniques for optimization purposes. Originally, RSM was developed to model experimental responses and then migrated into the modeling of numerical experiments. The difference is in the type of error generated by the responses. In physical experiments, inaccuracy can be due to measurement errors while in computer experiments, numerical noise is a result of incomplete convergence of iterative processes, round-off errors or the discrete representation of continuous physical phenomena. The application of RSM to design optimization is aimed to reduce the cost of expensive analysis methods (e.g. finite element method or CFD analysis) and their associated numerical noise [11]. As an application of RSM, Hatami et al. [11,12] applied it for optimizing the geometry of heat exchanger for more heat recovery. The main aim of this study is to optimize the geometry of asymmetric airfoil blades of a VAWT using RSM algorithm to reach the best efficiency for output power and lift force.

2. Problem description

As described above and due to reduction in fossil fuel reserves and increase in energy demands, renewable energy technologies such as wind energy turbines are widely considered by the researchers to improve their efficiency. Fig. 1 shows a vertical axis wind turbine and its schematic with five blades. In this paper, fifteen airfoil blades are suggested for this type of turbine (with three blade) to obtain the best geometry for this type of wind turbine. RSM optimization analysis is performed on the numerical outcomes form CFD modeling for these 15 cases blades in different rotor angular speed (350–600 rpm) and constant wind speed (8 m/s). The diagram shown in Fig. 2 clarifies the path of the solution to the problem until optimization.

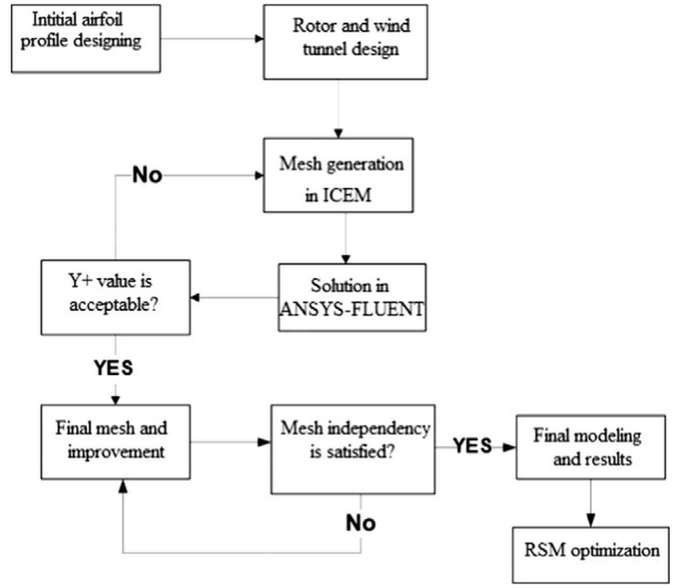

Fig. 2. Diagram of the problem solution.

3. Numerical analysis

The numerical simulation is performed with a two dimensional unsteady turbulent flow system. Governing equations are [6]:

Continuity equation:

$$\nabla.\left(\rho\vec{V}\right)=0 \tag{1}$$

Momentum equations:

x − momentum:

$$\frac{\partial(\rho u)}{\partial t}+\nabla.\left(\rho u\vec{V}\right)=-\frac{\partial p}{\partial x}+\frac{\partial\tau_{xx}}{\partial x}+\frac{\partial\tau_{yx}}{\partial y} \tag{2}$$

y − momentum:

$$\frac{\partial(\rho v)}{\partial t}+\nabla.\left(\rho v\vec{V}\right)=-\frac{\partial p}{\partial y}+\frac{\partial\tau_{xy}}{\partial x}+\frac{\partial\tau_{yy}}{\partial y} \tag{3}$$

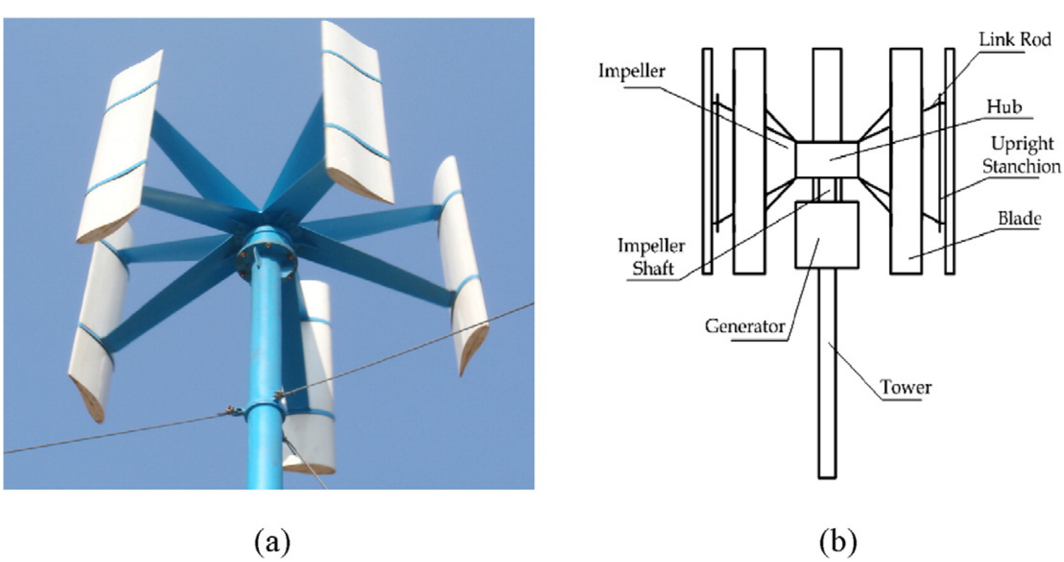

Fig. 1. a) Vertical axis wind turbine (VAWR) with five blade. b) Schematic of VAWR with details of components.