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Effect of rotor axial position on the aerodynamic performance of an airborne wind turbine system in shell configuration

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ABSTRACT

Wind energy has been one of the most widespread types of intermittent renewable energy harvesting source. Airborne wind turbine (AWT) stands out among other available techniques for harvesting wind energy because of its ability to operate at multiple times higher altitudes. This paper presents the aerodynamic performance of an AWT system at an altitude of 400 m with NREL Phase IV rotor position variation within the buoyant shell. The unsteady numerical simulations have been carried out at rotor axial positions of 0.25 L, 0.3 L, 0.35 L, 0.4 L and 0.45 L (L is the shell length) from the inlet, in order to investigate rotor torque variation in one complete rotor revolution. Additionally, steady-state simulations of the AWT system have been performed at various wind speeds (7 m/s–20 m/s) and yaw angles (0°–15°), to investigate the optimum aerodynamic performance of buoyant shell and rotor. Results demonstrate that by placing the rotor at the shell inlet (0.25 L) with step placed at the shell outlet, maximum torque enhancement of 25.3% can be attained at wind speed of 15 m/s. Buoyant shell exhibits equilibrium at 0° yaw angle due to symmetric pressure distributions on the shell body. Whereas for yaw angle > 0°, instability instigated by non-uniform pressure distributions results in the oscillation of shell. However restoring torque damps out these vibrations and provides assistance in re-establishing equilibrium position.

1. Introduction

Modern life is built on energy however, carbon emitting power industry has adversely affected the climate leading to the establishment of Paris agreement signed by 195 members of UNFCCC (United Nations Framework Convention on Climate Change) in December 2015 to mitigate greenhouse gas emissions [1]. A race is on all around the world to develop cleaner low-cost alternatives to fossil fuels. In this context, there has been a fast growth and spread of renewable energy plants. Among them, wind energy power plants are the most widespread type of intermittent renewable energy harvesters with their 486 GW of cumulative installed power by the end of 2016 [2]. Wind energy has 12.6% annual growth of installed capacity for the year 2015–16 and is solely capable of fulfilling 20% of global energy requirements by 2030 [3]. High altitude wind energy (HAWE) or airborne wind energy (AWE), an innovative green technology, is a viable solution of the changing climate and mounting power challenges. Affordable wind energy can be delivered to furthest points of the earth, powering remote communities, off-grid industries and disaster relief. The working principal of HAWE is similar to conventional AWE that power production from a wind turbine is cubic power of wind velocity ($P = f(v^3)$) [4]. However, attached to connecting flexible tether, Airborne wind turbines (AWT) operate at high altitudes of 500-15000 m in order to harnesses consistent, powerful winds and generate 10–100 times the power of a tower mounted turbine [5].

AWT technologies tested or modeled so far includes; high altitude kites [6,7], buoyant rotating cylinders [8], and gliders [9] and Buoyant airborne wind turbine (BAT) [10,11]. Except BAT all other technologies generate power in intermittent phases of production and recovery. Whereas in BAT, both turbine and generator are enclosed in helium filled airborne thus produce electricity in a continuous manner. The lightweight of BAT in addition to the lift provided by aerodynamic shape of ring shaped shell keeps the whole system afloat at elevations [12]. The least dependence of these self-regulating turbines on the wind direction also provides a solution for uncertainty and dependence of wind turbines on the wind pattern [13,14]. Furthermore, the ring shaped shell of BAT is similar to ducted wind turbines (DWT) and it further enhances the wind velocity along with the turbine stability even in strong continuous winds. In addition to shell aerodynamic shape [Abe and Ohya [15], Abe et al. [16], Frankovic and Vrsalovic [4], Lawn [17], Kannan et al. [18], Hu and Cheng [19], Van Bussel [20]] cord length, blade design and twist angle, the role of stepped duct can also

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Nomenclature

CP	power coefficient [–]
C_P	coefficient of pressure [–]
d	shell diameter [m]
h	altitude [m]
L	characteristic length [m]
n	number of nodes
p	pressure [Pa]
Re	Reynolds number
R	gas constant [J/kg K]
r_t	rotor tip radius [m]
r_m	mesh growth rate
T	temperature [K]
t	time [s]
u	velocity [ms^{-1}]
U	time-averaged velocity [ms^{-1}]
U_∞	free stream velocity [ms^{-1}]
$\acute{u}$	fluctuating part of velocity [ms^{-1}]

Greek symbols

α	turbulence modeling constant
δ_{ij}	Kronecker delta
ρ	density [kg/m^3]
τ	torque [Nm]
σ	diffusion coefficient [–]
ω	angular speed [rad/s]
τ	stress tensor [Nm^{-2}]
μ	viscosity [Pa s]

Sub and superscripts

m	mesh
min	minimum
o	sea level
out	domain outlet

significantly influence the efficiency of DWT [14].

In past, multiple researchers attempted to study aerodynamic characteristics of wind turbines by experimental and numerical means. However numerical methods provide a much reliable substitute of expensive experimental techniques because of recent advancements in the computational methods. Esfahanian et al. [21] proposed a hybrid CFD and BEM method to predict the aerodynamic performance by computing the flow field around a wind turbine rotor. Rio Vaz et al. [22] suggested and verified an improved blade element theory for DWTs. Their suggested approach had a shortcoming since it could not effectively calculate the induced velocity. In order to resolve this problem, they combined their modified blade element theory with conservation principles and CFD results. Optimization of blade twist angle and a chord length of DWTs was performed by Vaz and Wood [23], they suggested a model based on the extension of blade momentum theory. An extension of non-linear actuator disk theory was proposed by Bontempo and Manna [24] for ducted rotors, it provides the exact solution for axisymmetric, inviscid and incompressible flows. Bontempo and Manna compared the nonlinear and semi-analytical actuator disk method [24] with CFD actuator disk method [25,26], moreover, they applied the nonlinear and semi-analytical actuator disk method on the open and ducted wind turbines [27]. A study using semi-analytical actuator disk method and axial momentum theory was also carried out by Bontempo and Manna [28] for a ducted wind turbine. They concluded that the semi-analytical actuator disk method is more effective as it considers slip stream rotation, divergence and duct rotor interaction. Politis and Koras [29] proposed a lifting surface theory for duct modeling with lift line approach for rotor modeling. Recently, Bontempo and Manna [30] proposed the exact solution for equations involved in the axial momentum theory. They obtained a relation between power and thrust coefficients for the polynomial type load distributions. Moreover, Rezaeiha et al. [31,32] have performed detailed numerical study on wind turbines, they investigated the effect of pitch angle on the power performance and effect of shaft on the aerodynamic performance of vertical axis wind turbines. For horizontal axis wind turbine (HAWT) recently, Rezaeiha et al. [33] carried out an elaborate study addressing the fluctuations of lift coefficient, angle of attack and the resultant fatigue loads for large HAWTs. While, in other CFD methods [10,34–36], a differing approach to the aforementioned methods has been adopted, the flow is worked out by resolving a set of Navier-Stokes equations by discretization of whole wind turbine geometry into small elements or volumes. CFD allows computing the forces and moments among several other parameters such as dynamic stall, boundary layer transition, wake effects and unsteady aerodynamics [37–39].

Since BAT is a new emerging technology, so far merely aerodynamic characteristics of turbine shell have been recently studied by Saeed and Kim [10,11] for varying wind conditions. However, the position of the turbine within the airborne shell has not discussed explicitly. Moreover, the effect of turbine axial position on other aspects of AWT system in shell configuration is still unexplored. Therefore present research is aimed at steady and unsteady aerodynamic analysis of turbine

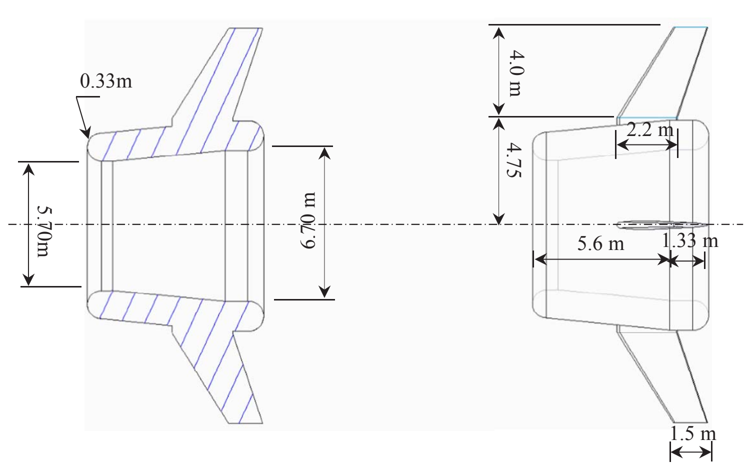

Fig. 1. Geometrical details of the airborne shell.