Renewable Energy 86 (2016) 770–784

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

A study on the aerodynamics of a floating wind turbine rotor

R. Farrugia [a, *], T. Sant [a], D. Micallef [b]

[a] University of Malta, Faculty of Engineering, Department of Mechanical Engineering, Msida, MSD 2080, Malta
[b] University of Malta, Faculty of the Built Environment, Department of Environmental Design, MSD 2080, Malta

ARTICLE INFO

Article history:
Received 16 October 2014
Received in revised form
27 May 2015
Accepted 25 August 2015
Available online xxx

Keywords:
Unsteady wind turbine aerodynamics
Floating offshore wind turbine
Free-wake vortex model

ABSTRACT

Understanding the impact of wave induced effects on the aerodynamic performance of Floating Offshore Wind Turbines (FOWTs) is crucial towards developing floating wind turbines cost-effectively to harness wind energy in deep water sites. The complexity of the wake of an FOWT has not yet been fully understood and both experimental together with numerical techniques are essential in this regard. An open source free-wake vortex code was used to determine whether experimentally-observed effects of the wave motions on floating rotor aerodynamics could be reproduced numerically by the lifting line method. From free-wake simulations on a large scale FOWT, complex wake phenomena were observed under the impact of extreme wave conditions. It was found that the difference between the mean power coefficient under platform surge conditions and the steady power coefficient depends on platform surge frequency, surge amplitude and the rotor operating conditions. Using the results from the free-wake vortex simulations, an analysis of a number of wind turbine wake characteristics under floating conditions was carried out in order to identify possible reasons behind the increase in the aerodynamic torque and thrust variations with tip speed ratio.

1. Introduction

Recently, there has been an increased interest among industry and academia to develop and commercialise floating wind turbine technologies. Floating wind turbines may offer a viable solution towards achieving large-scale renewable energy generation. It is believed that this technology would in the future offer enormous possibilities for harvesting wind energy in deep waters cost-effectively. A reduction in the life cycle costs of floating offshore wind turbines (FOWTs) can solely be achieved if the entire system design is optimised. However studies on the operating and failure design conditions which are unique to FOWTs have not yet been carried out with a high level of detail [1]. Such studies are crucial in determining whether conventional methods used in the modelling of fixed-bottom offshore and onshore wind turbines could be reliably adapted to model FOWTs.

A number of studies have been carried out on the hydrodynamic aspects namely the influence of the wave motion on the mooring-line and platform dynamics. However aerodynamic analysis is still based on the Blade Element Momentum (BEM) theory with incorporated models to correct for hub and tip losses, dynamic inflow and dynamic stall. Sebastian [2] showed that the effect of the platform motion on the rotor's aerodynamic performance is not described by the BEM theory in a physically realistic manner. Due to the limited amount of knowledge available, comparable rotor conditions allow the advanced aerodynamic models used in the helicopter industry to be implemented in the analysis of the wake formation of a floating wind turbine. An example of such models is the Generalised Dynamic Wake (GDW) method which is able to inherently model dynamic wake effects. However applicability of the GDW model is limited to relatively high wind speeds [3]. Potential flow methods, on the other hand, have been successfully applied by Sebastian and Lackner [4,5] to develop a free-wake code to simulate the wake development of a rotor oscillating under realistic platform motions.

2. FOWT wake aerodynamics

The helical tip vortex structure is generally the predominant feature determining wind turbine wake behaviour. At the tip region, the rotor blades have very large pressure gradients resulting in the tip vortices with high circulation strength and swirl velocities. The result is a strong rolled-up tip vortex originating from each individual blade [6,7]. Therefore it is important to understand

* Corresponding author.
E-mail address: russell.farrugia@um.edu.mt (R. Farrugia).

http://dx.doi.org/10.1016/j.renene.2015.08.063

Nomenclature

δ_v	Turbulent viscosity coefficient [-]
ε_{C_P}	Percentage difference between the instantaneous response and mean of C_P [-]
ε_{C_T}	Percentage difference between the instantaneous response and mean of C_T [-]
ε_Q	Relative torque error in free-wake results [-]
θ_{tip}	Blade tip pitch angle [°]
λ	Tip speed ratio [-]
ν	Air viscosity [m^2/s]
ω	Platform surge frequency [Hz]
Γ	Circulation strength of a vortex filament [m^2/s]
Γ_B	Bound circulation strength [m^2/s]
Γ_S	Shed circulation strength [m^2/s]
Γ_T	Trailing circulation strength [m^2/s]
Φ	Coefficient of sinusoidal fit equation: phase angle [°]
Ω	Rotor rotational frequency [Hz]
a_1	Axial wake induction factor [-]
a	Coefficient of sinusoidal fit equation: amplitude [m]
c	Coefficient of sinusoidal fit equation: frequency [Hz]
k	Reduced frequency [-]
$\boldsymbol{l}$	Vortex filament direction vector [-]
n	Vatistas equation power factor [-]
nx	Wake age cut-off point [-]
r	Radial distance of an arbitrary point from the vortex centre [m]
r_0	Initial vortex core radius [m]
r_c	Vortex core radius [m]
$uind_{shed}$	Lifting-line induced velocities because of shed vorticity [m/s]
$uind_{trail}$	Lifting-line induced velocities because of trail vorticity [m/s]
v	Instantaneous platform surge velocity amplitude [m/s]
v_{max}	Maximum platform surge velocity amplitude [m/s]
A	Platform surge amplitude [m]
C_P	Power coefficient [-]
C_T	Thrust coefficient [-]
N_b	Free wake discretization: number of blade nodes [-]
N_θ	Free wake discretization: blade azimuth angle [°]
N_{rev}	Free wake discretization: number of rotor revolutions [-]
Q	Rotor aerodynamic torque [Nm]
R	Blade tip radius [m]
Re	Reynolds number [-]
T	Rotor aerodynamic thrust [N]
$\boldsymbol{U}$	Flow velocity vector [m/s]
U_∞	Free stream velocity [m/s]
aoa	Angle of attack
BEM	Blade Element Momentum Theory
CFD	Computational fluid dynamics
DOF	Degree of freedom
FVM	Free wake vortex method
GDW	Generalised Dynamic Wake
$NREL$	National Renewable Energy
$FOWT$	Floating Offshore Wind Turbine
$RANS$	Reynolds averaged Navier stokes
RL	Ramasamy Leishman vortex core growth model
TLP	Tension Leg Platform
UoM	University of Malta

the physical development of the tip vortex and the impact that the velocity field in its vicinity has on the wake induced velocities at the rotor. In the case of FOWTs, the development of the tip vortices may differ from that of fixed-bottom wind turbines due to periodic changes in the wind relative to the rotor blades. Variations in the tip vortex pitch, rotor-to-wake and vortex-to-vortex interactions may lead to a higher uncertainty in determining the power developed by the wind turbine rotor. This paper will therefore seek to address the following questions:

1. Is there a change in the power and wake characteristics in the case of an FOWT compared to a fixed wind turbine?
2. Are these characteristics dependent on the wave characteristics and FOWT rotor operating conditions?

3. Free-Wake Vortex Simulations - WInDS Overview

An open source free-wake vortex code based on the potential flow theory was chosen since it models the physics needed to simulate the complex aerodynamics of a floating wind turbine at a low computational cost compared to Navier Stokes methods. The Wake Induced Dynamic Simulator (WInDS) was written by Sebastian and Lackner [2,5] from the University of Massachusetts with the aim of addressing the present lack of knowledge on the wake aerodynamic characteristics of floating wind turbines.

In vortex models the main assumption is that all vorticity is concentrated in the core of a vortex. Therefore the vortical wake is modelled by vortex lines and discretised using straight-line filaments. The induced velocity at a point contributed by a vortex filament in the wake is computed by the Biot-Savart Law defined by Equation (1). This representation is a valid assumption in low speed aerodynamics where compressibility is not an issue. Furthermore, on the basis of Prandtl's lifting line theory, in WInDS, the wind turbine blade is discretised radially by vortex filaments which make up the lifting line. The latter consists of a bound vortex from which the lift force can be deduced.

$$\mathbf{U} = \frac{\Gamma}{4\pi}\frac{d\mathbf{l}\times\mathbf{r}}{r^3} \tag{1}$$

In potential flow models, it is important to describe how the wake induced velocities are affected by the velocity field in the vicinity of a vortex and its physical development with vortex age have on the wake induced velocities [8,9]. Based on experimental observations viscous vortex models were devised primarily to provide the variation of the 2D tangential velocity, U_θ with radial distance from the centre of the vortex with core radius r_c. The Vatistas model given by Equation (2) is used in WInDS which is a general series of desingularised velocity profiles for vortices with continuous distributions of the flow quantities.

$$U_\theta(\bar{r}) = \left(\frac{\Gamma}{2\pi r_c}\right)\left(\frac{\bar{r}}{\left(1+\bar{r}^{2n}\right)^{1/n}}\right) \tag{2}$$

Vortex core growth models are implemented in the free-wake code to remove the singularity problem with the Biot-Savart law at $r = 0$. For the subsequent simulations carried out the Ramasamy-Leishman (RL) vortex core growth model given by Equation (3) was