Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia

Energy Procedia 94 (2016) 531 – 543

13th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2016, 20-22 January 2016, Trondheim, Norway

Aerodynamic modeling of floating vertical axis wind turbines using the actuator cylinder flow method

Zhengshun Cheng[a,b,c,*], Helge Aagaard Madsen[d], Zhen Gao[a,b,c], Torgeir Moan[a,b,c]

[a]*Department of Marine Technology, Norwegian University of Science and Technology (NTNU), Trondheim, NO-7491, Norway*
[b]*Centre for Ships and Ocean Structures (CeSOS), NTNU, Trondheim, NO-7491, Norway*
[c]*Centre for Autonomous Marine Operations and Systems (AMOS), NTNU, Trondheim, NO-7491, Norway*
[d]*Department of Wind Energy, Technical University of Denmark, Roskilde, 4000, Denmark*

Abstract

Recently the interest in developing vertical axis wind turbines (VAWTs) for offshore application has been increasing. Among the aerodynamic models of VAWTs, double multi-streamtube (DMST) and actuator cylinder (AC) models are two favorable methods for fully coupled modeling and dynamic analysis of floating VAWTs in view of accuracy and computational cost. This paper deals with the development of an aerodynamic code to model floating VAWTs using the AC method developed by Madsen. It includes the tangential load term when calculating induced velocities, addresses two different approaches to calculate the normal and tangential loads acting on the rotor, and proposes a new modified linear solution to correct the linear solution. The effect of dynamic stall is also considered using the Beddoes-Leishman dynamic stall model. The developed code is verified to be accurate by a series of comparisons against other numerical models and experimental results. It is found that the effect of including the tangential load term when calculating induced velocities on the aerodynamic loads is very small. The proposed new modified linear solution can improve the power performance compared with the experiment data. Finally, a comparison of the developed AC method and the DMST method is performed using two rotors and shows that the AC method can predict more accurate aerodynamic loads and power than the DMST method, at least for the considered rotors.

Peer-review under responsibility of SINTEF Energi AS

Keywords: Floating vertical axis wind turbine; aerodynamic modeling; actuator cylinder flow model; double multi-streamtube model

1. Introduction

During the 1970s and 1980s, vertical axis wind turbines (VAWTs) attracted interests of researchers mainly in USA and Canada and considerable efforts were devoted to investigate and develop the Darrieus VAWTs [9]. Commercial Darrieus VAWTs were also developed by the FloWind Corp. Due to the issues of severe fatigue damage and low power efficiency, VAWTs became less popular than horizontal axis wind turbines (HAWTs). However, as the wind farms are

* Corresponding author. Tel.: +47-73596004 ; fax: +47-73595528.
E-mail address: zhengshun.cheng@ntnu.no

Peer-review under responsibility of SINTEF Energi AS
doi:10.1016/j.egypro.2016.09.232

moving towards deeper waters where large floating wind turbines will be more economical, floating VAWTs have the potential to reduce the cost compared to floating HAWTs [8] and efforts devoted to investigate floating VAWTs are increasing.

Since Sandia National Laboratories started the study of vertical axis wind turbines in the 1970s, a variety of aerodynamic models have been proposed for VAWTs. These include streamtube models, actuator cylinder (AC) flow model, panel method, vortex method and computational fluid dynamics (CFD) method. The streamtube models are based on the conservation of mass and momentum in a quasi-steady flow. They equate the forces on the rotor blades to the change in the streamwise momentum through the turbine. They can be categorized into three models: single streamtube model (SST) [13], multi-streamtube model (MST) [12] and double multi-streamtube (DMST) [9] model. SST model [13] assumes that the entire rotor represented by an actuator disk is enclosed in one streamtube, MST model [12] extends the SST model by dividing the rotor into a series of adjacent streamtubes and DMST model [9] assumes that the vertical axis wind turbine can be represented by a pair of actuator disks in tandem at each level of the rotor. Up to now, the DMST model has been widely used to estimate the aerodynamic loads on VAWTs.

However, by considering a 2D VAWT rotor, Ferreira et al. [2] compares the different models for VAWTs, including the MST model, DMST model, AC [4] model, U2DiVA using panel model and CACTUS [7] using lifting line model, and reveals that the DMST model seems to be less accurate than the AC, panel and vortex models. An overview of these aerodynamic models can also be found in [11], which considers their complexity, accuracy, computational cost, suitability for optimization and aeroelastic analysis. Due to the considerations of accuracy and computational cost, the AC method seems to be the favorable method that can be used to conduct aero-hydro-servo-elastic time domain simulations of floating VAWTs.

The AC method is a quasi-steady Eulerian model developed by Madsen [4]. The model extends the actuator disc concept to an actuator surface coinciding with the swept area of the 2D VAWT. In the AC model, the normal and tangential forces Q_n and Q_t resulting from the blade forces are applied on the flow as volume force perpendicular and tangential to the rotor plane, respectively, as illustrated in Fig. 1. Thus the velocity induced by the normal and tangential forces Q_n and Q_t can be computed analytically.

The AC method has been implemented in HAWC2 [3] to conduct the fully coupled aero-hydro-servo-elastic time domain simulations of floating VAWTs. It can account for dynamic inflow, structural dynamics, tower shadow and dynamic stall. Paulsen et al. [10] performed a design optimization of the proposed DeepWind concept. An improved design has been obtained with an optimized blade profile with less weight and higher stiffness than the first baseline design.

In this paper, an aerodynamic code is developed using the AC method developed by Madsen [4] to model VAWTs for offshore application. The basic theory of the AC method will firstly be briefly presented. In the developed code, the linear solution of induced velocities will be derived by including the effect of tangential load. The effect of tangential load on the induced velocity was discussed in [5], but was ignored in the implementation of the AC method into HAWC2 [3,6]. Using the AC method, modeling of a VAWT is presented subsequently including the effect of dynamic stall via the Beddoes-Leishman dynamic stall model. Two different approaches are used to calculate the normal and tangential loads acting on the rotor . A series of simulations are conducted to verify the code by comparisons with other numerical models and experimental results . The accuracy of the present code and the effect of tangential load on the induced velocity are addressed. Finally, a comparison of the present AC method and the DMST method is performed.

2. Actuator cylinder flow model

Considering a 2D quasi-static flow problem as shown in Fig. 1, the basic equations are the Euler equation and continuity equation. For simplicity the equations are non-dimensionalized with the basic dimensions R, V_∞ and ρ, which are rotor radius, free stream velocity and flow density, respectively. The velocity components can thus be written as

$$v_x = 1 + w_x \tag{1}$$

$$v_y = w_y \tag{2}$$

where w_x and w_y are local velocities representing the changes in wind speed due to the presence of the VAWT.