Energy 99 (2016) 20–31

Contents lists available at ScienceDirect

Energy

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

Fundamental study on aerodynamic force of floating offshore wind turbine with cyclic pitch mechanism

Qing'an Li [a, *], Yasunari Kamada [b], Takao Maeda [b], Junsuke Murata [b], Kohei Iida [b], Yuta Okumura [b]

[a] Division of System Engineering, Mie University, 1577 Kurimamachiya-cho, Tsu, Mie 514-8507, Japan
[b] Division of Mechanical Engineering, Mie University, 1577 Kurimamachiya-cho, Tsu, Mie 514-8507, Japan

ARTICLE INFO

Article history:
Received 24 July 2015
Received in revised form
2 January 2016
Accepted 16 January 2016
Available online 10 February 2016

Keywords:
Floating offshore wind turbine
Aerodynamic forces
Cyclic pitch mechanism
Six-component balance
Wind tunnel experiment

ABSTRACT

Wind turbines mounted on floating platforms are subjected to completely different and soft foundation properties, rather than onshore wind turbines. Due to the flexibility of their mooring systems, floating offshore wind turbines are susceptible to large oscillations such as aerodynamic force of the wind and hydrodynamic force of the wave, which may compromise their performance and structural stability. This paper focuses on the evaluation of aerodynamic forces depending on suppressing undesired turbine's motion by a rotor thrust control which is controlled by pitch changes with wind tunnel experiments. In this research, the aerodynamic forces of wind turbine are tested at two kinds of pitch control system: steady pitch control and cyclic pitch control. The rotational speed of rotor is controlled by a variable speed generator, which can be measured by the power coefficient. Moment and force acts on model wind turbine are examined by a six-component balance. From cyclic pitch testing, the direction and magnitude of moment can be arbitrarily controlled by cyclic pitch control. Moreover, the fluctuations of thrust coefficient can be controlled by collective pitch control. The results of this analysis will help resolve the fundamental design of suppressing undesired turbine's motion by cyclic pitch control.

1. Introduction

The worldwide is faced with significant challenges in the energy sector such as energy shortage, environmental pollution, greenhouse gas emission and energy supply in rural areas, which severely restrict its sustainable development [1–3]. Renewable energy has been attracting attention worldwide in order to tackle these issues. Among the renewable technologies, the wind power has been developed all over the world because of its large-scale deployment and the excellent power generation efficiency [4–8]. With an average annual growth rate of 20% over the past 10 years, the total global wind power generation capacity reached 370 GW by the end of 2014 [9]. Nevertheless, due to more turbulent breezes and a lower annual mean wind velocity, it is technologically hard to achieve high-energy efficiency from onshore wind resources [10–12]. Therefore, the industry is advancing into deep water, and an increasing amount of effort is devoted to the study of Floating Offshore Wind Turbine (FOWT).

FOWT has experienced significant growth in recent years, and continues to expand worldwide [3,11,13]. However, FOWT is susceptible to large oscillations such as aerodynamic force of wind and hydrodynamic force of wave, which may compromise its performance and structural stability [14]. The research of FOWT is multidisciplinary, involving hydrodynamics, structural responses, aerodynamics, automatic control system, and so on [15–18]. Thence, evaluation of aerodynamic behaviors considering the automatic control system is one of the important factors in the process of optimization and design of the FOWT.

In recent years, many researches and universities focused on the development of FOWT and achieved a lot of significant achievements. Roald L. et al. [19] and Bayati I. et al. [20] proposed an analysis methodology to quantify the effects of second-order hydrodynamics forces on the FOWT, based on the methodology used in the offshore oil and gas industry. The proposed method relies mainly on simulation by the frequency-domain tool, and is based on the simulation methodology typically applied to more traditional offshore structures. Duarte T. et al. [21] also presented a computationally efficient methodology for the assessment of second-order hydrodynamic forces on FOWT. In their research, the contribution of wind and wave loads are studied within FAST

* Corresponding author. Tel.: +81 59 231 9658; fax: +81 59 231 1572.
E-mail addresses: li@fel.mach.mie-u.ac.jp, 434687517@qq.com (Q. Li).

http://dx.doi.org/10.1016/j.energy.2016.01.049
0360-5442/

Nomenclature

a	amplitude of blade pitch angle [deg]
A	swept area of wind turbine [m^2]
b	averaged blade pitch angle [deg]
c	airfoil chord length [m]
C_p	power coefficient ($=Q\omega/(0.5\rho DH)$)
C_{Mx}	tilt moment coefficient ($=Mx/(0.5\rho AR)$)
C_{Mz}	yawing moment coefficient ($=Mz/(0.5\rho AR)$)
C_T	thrust coefficient ($=F_T/(0.5\rho A)$)
F_T	thrust force [N]
M_X	tilt moment [N•m]
M_Z	yawing moment [N•m]
P_{ower}	power output [W]
Q	rotor torque [N•m]
R	rotor radius [m]
U_0	mainstream wind velocity [m/s]
U_{rot_H}	tip speed of rotor blade at high tip speed ratio [m/s]
U_{rot_L}	tip speed of rotor blade at low tip speed ratio [m/s]
α	angle of attack [deg]
ϕ	geometric inflow angle [deg]
λ	tip speed ratio ($=R\omega/U_0$)
θ	blade pitch angle [deg]
ρ	air density [kg/m^3]
ω	angular velocity of rotor [rad/s]
ξ	phase difference of blade pitch angle [deg]
ψ	azimuth angle [deg]
ψ_{dis}	phase difference of ψ_{Mmin} [deg]
ψ_M	moment axis azimuth [deg]
ψ_{Mmin}	averaged value of ψ_M [deg]

(fatigue aerodynamics structures turbulence). Results showing the hydrodynamic forces and motion response for these systems are presented, and compared to the effect of aerodynamic forces. In order to confirm the observations on a full-scale surging rotor, Micallef D. et al. [22] focused on the effects of the tip speed ratios on the thrust and power coefficients under the influence of surge motion, using an actuator disc Navier Stokes model, a Blade Element Momentum model and a Generalized Dynamic Wake model. It can be found that the dynamic wake effects are not important in low tip speed ratios. However, Farrugia R. et al. [23] found that FOWT operation at high tip speed ratios resulted in significant fluctuations in rotor aerodynamic loading. Moreover, at high tip speed ratios, clustering of the tip vortex increases given that the convection of the tip vortex was low, which has been investigated by Borg M. et al. [13].

Several researchers investigated a simplified method for the aerodynamic forces to minimize the computational time while maintaining acceptable accuracy. Jonkman J M. [10], Cermelli C. et al. [24] and Matha D. et al. [25] developed a hydrodynamic module and implemented it with the original aero-servo-elastic code FAST, which was initially developed for the dynamic analysis of land-based wind turbines. Jeon et al. [26] investigated the unsteady aerodynamic loads of FOWT with the VLM (vortex lattice method). The VLM gained an explicit sketch of the rotor wake by representing the spatial locations and strengths of the vortex. Moreover, Sebastian T. et al. [27] characterized the unique operating conditions that made aerodynamic analysis of FOWTs a challenge with FAST. It is shown that offshore floating wind turbines are subjected to significant aerodynamic unsteadiness FOWT. Shin [28] conducted a model test of the OC3-Hywind FOWT which was carried out in various sea states, including rotating rotor effect with wind. The test confirmed that natural frequencies of surge and pitch were not affected by rotor aerodynamic damping. Shi W. et al. [29] concluded that the jacket substructure was a good choice for the offshore wind farm. In order to capture the behavior of the moving surface oscillation, Seixas M. et al. [17] used a five-mass model with the consideration of stiffness torque, structure and tower, and found that the total harmonic distortion coefficient was lower than the 5% limit imposed by IEEE-519 standard.

In order to evaluate the dynamic motion characteristics, the blade pitch control strategy must be considered. In previous studies, Jonkman J M. et al. [30] discussed three distinct approaches to improve the pitch damping of wind turbine: feeding back the tower-top acceleration, pitching to stall and detuning the pitch controller gains. The calculation of these controllers showed that detuning the gains for the collective pitch controller was the simplest and most successful strategy, as it results in improved power and speed regulation, and marginally reduced platform pitch motion. This was also consistent with the work of Larsen T J. et al. [31] and Skaare B. et al. [32]. To reduce the platform and blade loads, Lackner M [33] investigated a method for controlling the collective pitch angle of the blades and reducing the platform pitch motion. As shown in this research, large reduction of fatigue loads can be found in the platform pitch motion and tower loads at the expense of small increases in the power and speed variability. A more detailed analysis of the relative advantages of an individual blade pitch control approach are presented in the work of Namik H. et al. [34,35], which used linear quadratic regulator with periodic gains, to control the platform pitch motion. By changing the blade pitch angle of each blade, the net effect of the controller is to generate a tilt moment at the rotor hub, which can then help control the platform pitch motion. Previous research aimed to improve the control method for floating wind turbines. Nevertheless, an effective control strategy is still not fully determined.

A research gap in the literature has been identified in relation to the rotor performance and the stability of the FOWT during rotation. In this paper, we indicated the aerodynamic force of FOWT with cyclic pitch mechanism in accordance with the International Electrotechnical Commission IEC-61400-3 standard for FOWT [36]. For the stability of the FOWT during rotation, the major objective of the present study is to show the case that the aerodynamic forces are controlled by cyclic pitch control in wind tunnel experiment. The idea of applying cyclic pitch control system to the wind turbine is supposed to decrease load of wind turbine. This paper discusses two distinct approaches to improve the pitch damping of wind turbine: steady pitch control and cyclic pitch control. Moreover, moment and force acts on model wind turbine are examined by a six-component balance. Finally, it also describes a simple dynamic model on the behavior of the blade and analyses the fluctuation of blade flap angle caused by a periodic pitch control. In this way, the results of this analysis could be obtained to better guide to resolve the fundamental design of suppressing undesired turbine's motion by cyclic pitch control.

2. Experimental apparatus

2.1. Wind tunnel and wind turbine

The wind tunnel experiment is carried out in Mie University - Fluid Engineering Laboratory's wind tunnel in Japan. The experiment is performed in an open-jet type wind tunnel with outlet diameter of 1.67 m. The wind tunnel is powered by a 37 kW electric