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Experimental investigation of the cyclic pitch control on a horizontal axis wind turbine in diagonal inflow wind condition

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ABSTRACT

Offshore wind power has huge energy potential. For deep water areas, FOWTs (Floating Offshore Wind Turbines) are sensitive to large oscillations due to the aerodynamic force of wind and the hydrodynamic force of wave. In the natural environment, the wind is usually unstable and characterized by the diagonal inflow wind. In this study, the potential of alleviating blade load variations induced by the cyclic pitch control evaluated under the condition of the diagonal inflow wind. An experiment in an open wind tunnel was performed to investigate the effect of the diagonal inflow wind on the aerodynamic forces of FOWTs. A two-bladed downwind FOWT with a diameter of 1.6 m used for this experiment. The forces and moments applied to the entire wind turbine were measured by a six-component balance. A swash plate used to adjust the pitch angle in the cyclic pitch control. From the experimental results, the average value of the aerodynamic load acting on the rotor face in the diagonal inflow wind condition at phase angle of $\xi = 60^\circ$ equals the moment coefficient in the optimum operating condition at the front inflow wind. The load change on yaw system can be controlled by cyclic pitch control method.

1. Introduction

The suitable land sites with good wind potential have become scarce. Floating wind turbines can be used in deeper water and allow offshore wind turbines to be installed in more areas. It is also possible that larger turbines may be transported, deployed and decommissioned at a lower cost [1–3]. Thence, offshore wind energy is one of the key research and development directions in the wind energy industry [4]. Musial et al. [5] suggested that the offshore wind energy had a potential to become a major source of energy in the world, because the offshore had higher wind velocity, lower turbulence intensity and also could reduce visual and noise impacts. Mean-while, the offshore wind tends to be faster, steadier and has more advantages than onshore wind [6,7].

2015 was a huge year for offshore wind installations and the newly installed capacity was nearly 3.4 GW across five markets globally. This brought total offshore wind installed capacity to over 12 GW [8]. However, the FOWTs are susceptible to large oscillations and complex motion of floating platform such as the aerodynamic forces of the wind and the hydro-dynamic forces of the waves in the sea [9]. These factors may cause undesirable effects on the performance and structural stability of the wind turbines [10]. In addition, the wind direction and wind velocity constantly change in the sea on which the FOWTs are running, and the wind turbines sometimes accept a natural flow which does not directly face the rotor surface. Therefore, the evaluation and knowledge of these aerodynamic effects are necessary to solve the design and optimization issue of the offshore wind turbines in the diagonal inflow wind.

Presently, the wind turbine manufacturers are involved in producing wind turbines with higher rated power which means the rotor with larger diameter. Increasing the rotor diameters also introduces an asymmetric loading of the rotor blades [11,12]. Many control techniques have been proposed to reduce the effect of fatigue and load on the wind turbine. A control method is to use a technology originally known from helicopter control, cyclic pitch control, and later adapted to wind turbine control as reported in Refs. [13–16]. This type of regulator is based on the local blade load measurement, which is well-known as state-of-the-art technology.

In the last decade, the ability of cyclic pitch control systems to lower fatigue loading on wind turbines has been thoroughly investigated and quantified, as witnessed by a significant body of

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Nomenclature

A	wept area of wind turbine [m^2]
a	amplitude of blade pitch angle [deg]
b	average blade pitch angle [deg]
c	airfoil chord length [m]
C_{P}	power coefficient
C_{T}	thrust coefficient
C_{Mx}	pitching moment coefficient
C_{Mz}	yaw moment coefficient
N	number of blades
M_{x}	pitching moment [Nm]
M_{z}	yawing moment [Nm]
P	power output [W]
Q	rotor torque [Nm]
R	rotor radius [m]
T	thrust force [N]
U	mainstream wind velocity [m/s]
x	longitudinal coordinate [m]
y	lateral coordinate [m]
z	vertical coordinate [m]
α	angle of attack [deg]
θ	pitch angle [deg]
λ	tip speed ratio
ρ	air density [kg/m^3]
ω	angular velocity of rotor [rad/s]
ψ	azimuth angle [deg]
ξ	phase difference of blade pitch angle [deg]

literature devoted to this subject [17–19]. Traditionally, the cyclic pitch control is used for the three-bladed turbines to alleviate the blade loads by varying the 1P sinusoidal pitch angle of 120° between each blade. The cyclic pitch control is traditionally used for the three-bladed turbines to alleviate the blade loads by a 1P sinusoidal pitch variation phase shifted 120° between each blade [15,16,20].

In this paper, a periodic loading of the rotor is considered. The periodic loading appears on the blades with the rotation of the turbine rotor. This periodic loading has a number of harmonics with a first/dominating harmonic at the frequency of the wind turbine rotational speed in Ref. [21]. Bottasso et al. showed that the cyclic pitching of the blades induced a reduction of the average loading of a wind turbine, at least for some components such as the main bearing, the yaw bearing, or the tower [22]. So, the aim of this control method is to reduce the amplitude of the load at the frequency of the wind turbine rotational speed.

To mitigate these asymmetric loads, active load mitigation methodologies can be applied. One such methodology is individual pitch control (IPC) [23] in which the blades are pitched cyclically along their longitudinal axis. Houtzager studied and developed individually pitch-controlled blades by proposing a lifted repetitive controller that can reject these periodic load disturbances for modern fixed-speed wind turbines and modern variable-speed wind turbines operating above-rated [24]. Furthermore, Menon and Ponta focused on the use of rapid pitch control for handling short-term variations in wind conditions and load fluctuations within one cycle of rotation, with special attention to the prognosis of the aero-elastic response of the rotor [25]. Van Solingen et al. used linear individual pitch control method to significantly reduce the wind turbine loads for both below-rated and above-rated operation [26].

Moreover, Luhmann and Cheng [27] showed a significant reduction of the teeter angle excursion during normal operation and extreme gust situations of the two-bladed downwind wind turbine. The interaction of the teeter based cyclic pitch controller and the teeter dynamics is investigated. Li Q. et al. [28] presented the effect of pitch angle at fundamental performance experiment and the aerodynamic forces of wind turbine at pitch control experiment. In that experiment, the aerodynamic forces of wind turbine were estimated under front inflow wind condition. Therefore, the evaluation of the aerodynamic behaviors in the diagonal inflow wind condition is necessary and corresponding to the real operation of the wind turbine.

In addition, among other control methods, Bak et al. [29,30] conducted wind tunnel tests on a Risø-B1-18 airfoil with an adaptive trailing edge flap. In this study it was demonstrated that in some cases the maximum load reduction could be up to 80% by properly controlling the trailing edge. The wind tunnel tests performed by Velte et al. [31] also showed a similar tendency. Bottasso et al. [32] introduced passive control method using aeroelastic devices.

The previous studies related to yaw control have primarily focused on increasing the power capture through improved yaw alignment such as in Refs. [33,34] et al. It has been shown that the yaw behavior of a turbine has a significant impact on its overall structural loading, and this effect is more dominant for turbines with highly flexible support structures [35]. In the works of Mikkelsen et al. [36] and Pedersen et al. [37], large static yaw errors were observed on megawatt (MW) size onshore turbines that indicated a potential for increased power capture by improved yaw alignment. In the work of Kragh et al. [38], it was shown that the potential of alleviating blade load variations could be controlled by yaw misalignment. Navalkar et al. simulated individual pitch control for yaw control [39]. And Lee et al. presented that the minimizing load imbalance through the adjustments of yaw misalignment and collective pitch angle were implemented for the rigid and flexible blades under the sheared inflow [40].

While the majority of offshore wind turbines today are upwind in configuration, there have been an increased number of downwind offshore wind turbines that were designed and tested in recent years. As the rotor is oriented downstream of the nacelle, the downwind turbines have several advantages over the upwind turbines. Due to the restoring yaw moment resulting from the rotor thrust, downwind turbines have a natural tendency, comparable to a weathervane, to align themselves with the inflow [41]. Furthermore, the blockage effect of the downwind turbine's nacelle accelerates and redirects the incoming flow into the rotor, resulting in up to 3% higher power for a downwind turbine compared to an upwind turbine [42]. The downwind offshore wind turbine projects was performed in the industries and projects such as 2-B Energy [43], Ming Yang Wind Power [44], the Fukushima FORWARD project [45,46], Hitachi Ltd. [47], et al.

Thence, the paper will introduce the experiment performed in an open wind tunnel to assess the aerodynamic force of floating offshore wind turbines. The objective of this study is to estimate the potential of reducing the blade load variations of the two-bladed downwind wind turbine using cyclic pitch control in the diagonal inflow wind condition. Moment and force acting on model wind turbine are measured by a six-component balance. The paper is structured as follows. Section 2 presents the experimental apparatus and method. Section 3 is the results and discussion.