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Numerical investigation of vertical-axis tidal turbines with sinusoidal pitching blades

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ABSTRACT

In this paper, numerical simulations are conducted to compare the performances of a fixed-blade vertical-axis turbine (VAT), and a variable pitch VAT whose blades are forced to do sinusoidal pitching. The numerical model is based on the Navier-Stokes equations and shear stress transport (SST) k-ω turbulence model. At first, the output characteristics of fixed-blade turbines and variable pitch turbines with different amplitude of pitching, including power coefficient, torque coefficient and ripple factors, are compared. Then the hydrodynamic torques, tangential and normal forces on a blade are compared as well. The comparison reveals that sinusoidal pitching of the blades greatly improves the performance of the turbine. With an appropriate amplitude of pitching, not only the power efficiency increases, but the fluctuation in power output, rotation speed and torque output are suppressed as well. Results also show that the hydrodynamics forces on a blade of a variable pitch turbine are lower than those of the fixed-blade turbine.

1. Introduction

So far it seems that horizontal-axis wind turbines have won the competition with vertical-axis wind turbines in the large-scale wind power industry. However, in the field of tidal stream energy exploitation, it is still too soon to make a conclusion about their competition. Some advantages of VAT's that seem not so critical for wind turbines become more significant for tidal turbines. These advantages include structural simplicity, adaption to flow of arbitrary direction, the ability to transmit torque directly above the water surface, *etc*. The latter perhaps is the most significant one because it greatly reduces maintenance costs since no underwater working is needed any more. A straight-blade vertical-axis turbine, often referred to as H-Darrieus turbine, is one of the most popular vertical-axis turbines due to its easy manufactured blade and good performance. These turbines have been the objectives of several studies such as, for instance, the work of Gosselin (2015) and Gosselin et al. (2016), in which parametric study on the effects of rotor solidity, blade thickness, fixed pitch angle, and blade aspect ratio *etc.* to the performance of the turbine were carried out. These turbines achieve maximum power efficiency at an optimal tip-speed ratio (TSR) and solidity for a given flow condition; higher solidity reduces peak efficiency and lowers the optimal TSR, but helps to improve the poor self-starting performance to some extent; the angle of attack of blade varies periodically due to its motion on a circular path and introduces vibrations into the shaft torque and rotation; using more blades helps to reduce torque and rotation fluctuations.

The disadvantages of Darrieus turbines compared to the horizontal-axis turbine are, for instance, the relative lower overall efficiency, higher fluctuation in torque and rotational speed, inability to self-start reliably, a narrower band of tip-speed ratios to achieve good efficiency, and that the blades experience large angle of attack variation. Some efforts have been made to overcome the disadvantages of conventional H-Darrieus turbines. For example, the turbine could be incorporated with a duct to increase power output and reduce the torque fluctuation substantially. However, the cost of building a duct device is much greater than that of the turbine itself, due to its large size and hence the large hydrodynamic load that it experiences. Unless serving also as support structure, building a duct device only for the purpose of performance improvement is not economically feasible. Gorlov (1995, 1998) developed a novel turbine which uses helical twisted blades. By distributing the blade sections over a large fraction of the circumference of its circular path, the Gorlov helical turbine is reported to have greater efficiency, no torque fluctuation, and improved self-start performance. However, to manufacture a helical twisted blade is more complicated and, hence,

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more expensive than a straight blade. Furthermore, the angle of attack of fixed helical blades cannot be adjusted to avoid stall.

It has been found that the performance of a H-Darrieus turbine can be greatly improved, especially if the turbine operates at lower tip-speed ratio, by allowing the blades to pitch cyclically, so as to avoid stall and maintain favorable angles of attack as long as possible. The optimal pitch angle is a function of both the azimuthal position and the tip-speed ratio of the blade. The mechanisms for achieving pitch variation fall into two categories. One is active or forced pitching, which means that the blade is forced to pitch according to some predetermined schedule. Another is passive, or so-called self-acting pitching, which means that the blade is free to pitch under the interaction between the fluid dynamic force, the inertial force, and stabilizer moments. Passive variable pitch requires many fewer mechanical parts.

According to Kirke and Lazauskas (1991), both active and passive variable pitch concepts for vertical-axis wind turbines were already known in the late 1970s, but no performance data for actual prototypes had been published until early 1990s. Since then a lot of works on variable pitch wind turbines have been reported. Kirke and Lazauskas (1991) developed the earliest mathematical model based on an extended double-multiple streamtube (DMS) approach to predict the performance of passive pitch systems. Similar mathematical models have been adopted in later investigations such as, for instance, those of Lazauskas (1992), Staelens et al. (2003), Paraschivoiu et al. (2009), and Chougule and Nielsen. (2014). More complex models have also been introduced to get more accurate prediction of flow behavior around blades, *e.g.* the vortex model in Erickson et al. (2011), the RANS models in Miau et al. (2012) and Gosselin (2015) *etc*. Many researchers conducted wind tunnel experiments to confirm their predictions with mathematical models as, for instance, Kirke and Lazauskas (1993), Erickson et al. (2011). Most recently, Kirke and Paillard (2017) use both DMS model and 2-D RANS model to predict the performance of a vertical axis wind turbine in both fixed and variable pitch modes, and compared with field test data. They revealed that variable pitch enables to overcome two major disadvantages of normal fixed pitch vertical axis wind turbines, i.e. self-starting and overspeed control.

The strategies of variable pitch have been the objective of many studies. For active pitch control, pitch variation allow the blades to operate always at the optimal angle of attack for every azimuth position, but this control imposes high complexity on the system. Two simpler options to decrease the occurrence of dynamic stall are: either to maintain the blades' angle of attack on a predetermined angle as long as possible, or to make the blades' pitch angle following a sinusoidal variation. Lazauskas (1992) analyze the performance of vertical-axis wind turbines with three variable pitch mechanisms, a sinusoidal forced pitch variation, and two kinds of self-acting stabilized pitch controls. He reported that all the pitch control systems examined can be configured to produce a better starting torque, a broader operating range and greater efficiency than a fixed pitch turbine. Staelens et al. (2003) presented three strategies for actively varying the pitch angle. The first two require accurate control to keep the angle of attack under the stall angle, while the last one aims to adjust the pitch angle following a simple sinusoidal function. The authors conclude that although the power output obtained by using sinusoidal pitching is less than the other two strategies, it doesn't present any physical and mechanical difficulty and thus it is most practically feasible. As a further develop to Staelens et al. (2003), Paraschivoiu et al. (2009) use a genetic algorithm optimizer to find the optimal pitch variation which relating the blades' pitch to the local flow conditions along their circular path. The results show that a pitch variation is optimal only for a given TSR. Using a strategy to ensure an almost constant angle of attack during the whole cycle of blade motion, Gosselin (2015) report that the overall efficiency of a Darrieus turbine operating at tip-speed ratio 3.4 could exceed by 50% that predicted by a two-dimensional RANS model.

The concept of variable pitch blades is logically transferred from wind turbines to tidal turbines. Gosselin (2015) concludes that variable pitch is not particularly efficient for wind turbines that have low solidities and operate at high tip-speed ratios. For a hydrokinetic turbine operating at lower tip-speed ratios, the gain from variable blade pitch could be much larger. While the typical optimal tip-speed ratio for vertical-axis wind turbines usually ranges from 4 to 6, Salter (2005) suggests that the tip-speed ratio of vertical-axis tidal turbines should be less than 2.5 to avoid serious cavitation effect. Schönborn and Chantzidakis (2007) suggest a relative velocity between the blades and the water below 8.45 m/s to avoid cavitation for a symmetric NACA0018 blade. The lower tip-speed ratio of tidal turbines makes variable pitch particularly attractive. Due to their mechanical simplicity, passive variable pitch turbines have been the first to be tested at sea. A 50 kW Italian Kobold vertical-axis turbine with self-acting variable pitch straight blades has been installed at sea in 2001. Coiro et al. (2005) analyze the performance of the Kobold turbine with a DMS model. The theoretical predictions are in good agreement with the results from laboratory tests and sea trails. Hantoro et al. (2011) carried out experimental investigations on the performance of a passive variable pitch turbine in a towing tank and confirmed the enhanced ability to start rotating at intermediate TSRs and the lowered occurrence of stall. Lazauskas and Kirke (2012) used a memetic algorithm to optimize pitch parameters for passive pitch control systems. A DMS type model predicts that the peak efficiency is about 50% higher than an equivalent fixed pitch turbine. Self-starting ability and vibration performance are greatly improved as well.

Along with the progress of electromechanical equipment and automatic control technology, the cost and reliability of active pitch control are set to improve and achieve an acceptable level. Active variable pitch can always optimize the pitch angle of blades according to flow condition, while the parameters of a passive variable pitch can only be changed with difficulty once they have been set. Therefore, theoretically the former should let the turbine achieve better performance than the latter. Pitch actuation for active variable pitch vertical-axis turbine consumes significant power. Salter and Taylor (2007) suggest that if the pivot of the blade pitching is properly placed ahead of the center of pressure, then blade pitch movement will generate power rather than consuming it. This produced power partially compensates for the consumed power, so that the mean power needed to actuate the blades during a turbine's revolution is minimal. Paillard et al. (2013) incorporate a dynamic stall model into a streamtube model to investigate the performance of a Darrieus turbine with active pitch variation. A maximum increase on the power coefficient of 53% is reported for a sinusoidal pitch variation, when the power consumption required for blade pitching is lower than 1%. A general discussion on the performance of variable pitch hydrokinetic turbines can be found in Kirke and Lazauskas (2008, 2011).

Beside those focused on pitch control strategy, there are also studies on mechanic devices that actuating the blades such as, for instance, Grylls et al. (1978) and Vandenberghe and Dick (1986) for wind turbines, and a novel hydraulic control mechanism in Schönborn and Chantzidakis (2007) for tidal turbine in marine environment.

In this paper, numerical simulations based on a two-dimensional incompressible viscous flow model are carried out to further investigate the performances of a fixed-blade turbine and an active variable pitch turbine whose blades are forced to do sinusoidal pitching are compared. The output characteristics of fixed and variable pitch turbines with different amplitude of pitching are compared; the variations of power coefficient, torque coefficient, ripple factors, hydrodynamic torques, tangential and normal forces on a blade are discussed. To the knowledge of the authors, the rotational speed is always set to a series of constant values in existed numerical investigations on vertical-axis turbines. Differently from existed studies, in this paper the rotational speed is obtained by solving the motion equation at every time step, so that the influence of variable pitch on the rotational speed could be assessed as well. The effect of variable pitch to the hydrodynamic forces on the blades is also hardly found in existed studies, whilst it is a focal point of this paper, too.