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Numerical investigation of the influence of blade helicity on the performance characteristics of vertical axis tidal turbines

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ABSTRACT

Previous research has shown that helical vertical axis turbines exhibit lower torque fluctuation levels than straight-bladed turbines; however little is known of the impact of blade helicity on turbine performance characteristics. To investigate these relationships the hydrodynamic characteristics of straight and helical-bladed vertical axis turbines were investigated using Three-Dimensional (3D) Computational Fluid Dynamics (CFD) models using a commercial Unsteady Reynolds Averaged Navier-Stokes (URANS) solver. Simulations of power output, torque oscillations, and mounting forces were performed for turbines with overlap angles from 0° to 120° and section inclination angles from −15° to 45°. Results indicated that straight-bladed turbines with 0° blade overlap generated the highest power output. Helical turbines were found to generate decreasing power outputs as blade overlap angle increased due to the resultant blade inclination to the inflow. Blade section inclination to the inflow was also found to influence power output. Some benefits of helical-bladed turbines over their straight-bladed counterparts were established; helical turbine torque oscillation levels and mounting forces were reduced when compared to straight-bladed turbines. For both straight and helical-bladed turbines maximum mounting force levels were found to exceed the average force levels by more than 40%, with large cyclical loading forces identified.

1. Introduction

Straight-bladed vertical axis turbines, as proposed for tidal power generation, experience significant torque oscillations as a result of changing angles of attack on the blades as they rotate [1–3]. These oscillations generate alternating loading forces on the turbine structure that can lead to premature failure through fatigue if not adequately accounted for [4,5]. Research using Experimental Fluid Dynamics (EFD) has demonstrated that the use of helical-bladed turbines can reduce torque oscillation levels [4,6,7], as the flow does not concurrently stall along the full blade length due to the blade distribution around the rotational axis [8]. However helical blade overlap, ϕ, shown in Fig. 1, may influence power generation due to the inclination of the helical blades to the inflow. To investigate any relationships between these factors two approaches can be utilised: EFD or numerical simulation using methods such as Computational Fluid Dynamics (CFD).

Although EFD testing results concur that helical-bladed turbines exhibit reduced torque oscillation levels [4,6,7], there is general disagreement about the effects of helicity on power output. Shiono et al. [6] tested a series of straight and helical-bladed turbines with NACA633018 blade sections of the same overlap angle but differing turbine spans. They demonstrated that helicity decreased power output, and concluded that it was more appropriate to use straight rather than helical-bladed turbines to maximise power output. Niblick [7] performed EFD testing on two helical turbines with three and four NACA0018 blades of differing helicity. Results indicated that power output reduced as helicity increased, as the helicity reduced total lift and hence torque. However, Gorlov [9] compared the power outputs of a straight and 60° helical-bladed turbine of the same radius and height, determining that the helical turbine demonstrated increased power output over the straight-bladed design, in excess of 50% at some rotational rates. Gorlov also noted improvements of up to 95% greater power and 50%

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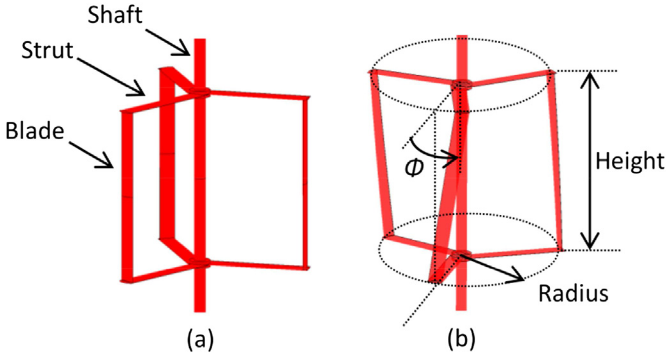

Fig. 1. Straight (a) and helical (b) bladed vertical axis turbines, including the definition of the helical blade overlap angle, ϕ.

higher speed in comparison with a straight-bladed turbine of identical overall dimensions during EFD testing of 20 small 0.09 m diameter models [4]. The reasons that Gorlov found power output to increase with blade overlap yet Shiono et al. and Niblick found power output to decrease are unknown, and were a key driver for this research.

Numerical CFD studies of helical vertical axis turbines are limited as Two Dimensional (2D) models cannot be utilised due to the curved blade geometry, resulting in computationally demanding simulations due to the resultant large mesh element counts associated with Three Dimensional (3D) simulations. Castelli and Benini [10] performed 3D CFD studies on a series of 1.03 m span single blades with overlap angles of 0°, 30°, 60°, 90° and 120°. Using the Unsteady Reynolds-Averaged Navier–Stokes (URANS) equations and the k-ω Shear Stress Transport (k-ω SST) turbulence model they found that power output reduced as blade overlap angle increased. Hall [11] simulated the power output of two single and four bladed helical turbines and compared results with EFD [7] using the URANS k-ω SST turbulence model. Power output was obtained at three rotational rates but was found to over predict the measured results by more than 30%. This simulation error was prescribed to the poor modelling of dynamic stall over the blades by the k-ω SST turbulence model. Studies of the effects of helicity on power output are limited with no comprehensive examinations found in literature.

The influence of blade helicity on power output, torque oscillations, and mounting loading forces were predicted using time-accurate 3D CFD models to allow the establishment of relationships between turbine blade shape and performance characteristics. To ensure numerical simulation accuracy, validation studies were performed on three turbine models to ensure that the CFD models accurately captured the influence of blade geometry on turbine performance characteristics.

2. Turbine geometry

Eight 3D CFD models were developed to investigate the influence of helical blade overlap and section inclination on turbine performance characteristics. The baseline 0° (straight-bladed) turbine design was geometrically identical to a previously tested EFD turbine [12] to permit validation of the modelling techniques utilised. The turbines were designed with ascending blade overlap angles of 0°(straight-bladed), 15°, 30°, 60° and 120° as shown in Tables 1, 2, allowing the direct characterisation of blade overlap with power output, torque fluctuation levels, and mounting forces. The same blade profile was used for all overlap turbines in this series. However, to investigate the influence of blade section inclination, five 15° blade overlap models with blade sections inclined by −15°, 0°, +15°, +30°, and +45° from the horizontal rotation plane were also developed as shown in Fig. 2.

To ensure the accuracy of the numerical methods utilised, validation studies were performed for two straight and one helical-bladed turbines, with all geometrical details shown in Tables 2, 3 [12–14]. All validation studies were performed at full-scale to ensure that the results were influenced by neither scaling nor Reynolds number effects. The 0° and 0°A turbines differed in strut section and strut location, allowing validation of geometrical changes against EFD results [12].

3. Numerical simulation methodology

Turbine power output, torque fluctuation levels, and mounting loading were simulated using transient time-accurate 3D CFD models using ANSYS CFX [15], which solved the incompressible fully turbulent URANS equations using an element-based finite volume method. Several performance parameters were investigated to enable the quantification of turbine efficiency and loading characteristics. Turbine power output was evaluated as the power coefficient, C_p, given by,

$$C_p = \lambda C_m \tag{1}$$

where tip speed ratio, λ, was defined as,

$$\lambda = r\omega/V \tag{2}$$

where ω was the turbine rotational rate, r was the turbine radius, and V was the inflow velocity. The turbine torque coefficient, C_m, was determined as,

$$C_m = \frac{Torque}{0.5\rho V^2 Sr} \tag{3}$$

where ρ was the water density (set to 997 kg/m^3 for all simulations), S was the turbine frontal area, and the *Torque* generated by the turbine was taken from the respective CFD or EFD results.

The k-ω SST turbulence model was utilised due to its ability to accurately model both free stream and boundary layer regions as well as offering improved prediction of flow separation and adverse pressure gradients by the inclusion of transport effects into the formulation of the eddy-viscosity [16], with the k-ω SST CFD turbulence model commonly used for vertical axis turbine simulations [2,10,17–21]. To ensure numerical accuracy and stability, all simulations were performed using a bounded second order upwind biased high order advection scheme along with an unbounded second order backwards Euler transient scheme [15]. Simulations using a first order upwind advection and first order backwards Euler transient scheme resulted in extremely poor resolution of C_p. Convergence was deemed achieved when solution residuals reduced to below 10^{-4} and reduced by more than three orders of magnitude. Additionally convergence was confirmed by ensuring that the final C_p determined was within 5% of the previous rotations results, required due to the periodic nature of C_p. An example of C_p convergence for the 0° turbine is shown in Fig. 3, where C_p values converged after approximately 3600 time steps, corresponding to 9 rotations. To reduce overall simulation times all simulations were started using previous results if available.

All turbine models were meshed using unstructured tetrahedral elements using ANSYS CFX 13.0 [15] and included all blades, struts, hubs, and the shaft. Mesh resolution was set by specifying the mesh size and growth rates to allow for local refinement of mesh zones. Mesh density was varied according to expected flow curvature rates