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Numerical simulation of the loading characteristics of straight and helical-bladed vertical axis tidal turbines

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A B S T R A C T

The stress and deflection of straight and helical-bladed vertical axis turbines was investigated using hydrodynamic and structural analysis models. Using Double Multiple Streamtube (DMS) and Computational Fluid Dynamics (CFD) models, the hydrodynamic forces and pressures on the turbines were modelled for three rotational rates from startup to over speed conditions. The results from these hydrodynamic models were then used to determine stress and total deflection levels using beam theory and Finite Element Analysis (FEA) methods. Maximum stress and deflection levels were found when the blades were in the furthest upstream region, with the highest stresses found at the blade-strut joints for the turbines studied. The helical turbine exhibited on average 13% lower maximum stress levels than the straight-bladed turbine, due to the helical distribution of the blades around the rotational axis. All simulation models offered similar accuracy when predicting maximum blade stress and deflection levels; however for detailed analysis of the blade-strut joints the more computationally demanding CFD-FEA models were required. Straight-bladed, rather than helical turbines, are suggested to be more suited for tidal installations, as for the same turbine frontal area they produce higher power output with only 13% greater structural stress loading.

1. Introduction

Existing studies of vertical axis turbines used for ocean power generation have concentrated primarily on hydrodynamics rather than structural analysis, as researchers have sought to maximise power output. To ensure longevity in marine environments however, detailed knowledge of turbine structural loading characteristics must be established. Although possible using strain gauges, Experimental Fluid Dynamics (EFD) studies to obtain loading are rarely performed. This fact, when combined with a general lack of turbine development over the last 15 years for both wind [1] and tidal turbines, has limited turbine usage. However, knowledge of turbine hydrodynamics and structural characteristics can be obtained by numerical simulation using methods such as coupled Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) codes. Additional research into both hydrodynamics and structural characteristics using numerical techniques will further understanding of turbine operational characteristics.

Both straight and helical-bladed designs, as shown in Fig. 1, are proposed by various researchers to generate power from the ocean's kinetic energy [2–5]. The designs differ in blade helicity, defined by the blade overlap angle Φ shown in Fig. 1. Straight-bladed turbines have 0° blade overlap, whereas helical turbines use blades that are distributed around the rotational axis at a defined overlap angle of Φ. Previous research by the authors indicated that straight-bladed designs generated higher power output when compared to helical turbines of the same frontal area and blade section as a result of the inclination of the helical turbines blades to the inflow [2]. Conversely, helical turbine torque oscillation levels and mounting forces were reduced when compared to straight-bladed turbines, due to the distribution of the turbine blades around the rotational axis [2]. Comparisons of the influence of these factors on the structural loading characteristics of the two designs is currently unknown, as previous research into loading characteristics has concentrated primarily on straight-bladed turbine designs.

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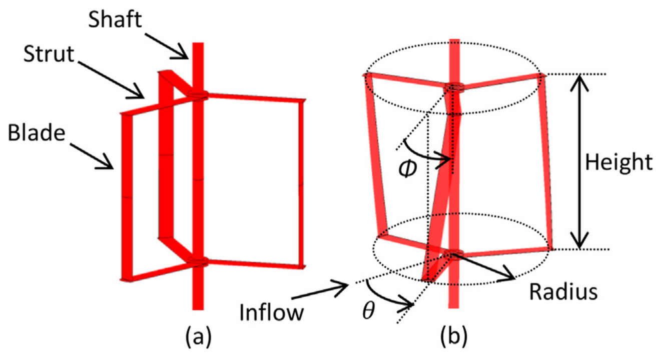

Fig. 1. Straight (a) and helical-bladed (b) vertical axis turbines, showing definitions of azimuth rotational angle θ, and blade overlap angle Φ.

Characterization of vertical axis turbine loading properties can be performed numerically by coupling Double Multiple Streamtube and CFD models with beam theory or FEA analysis methods [3–6]. However, considerable knowledge gaps exist in the characterisation of structural loading. Previous numerical studies have often been limited to either helical or straight-bladed designs [3–6], with no comparison between loading characteristics of the two designs performed. These works have often concentrated on blade loading, with no determination of the loading of the struts and blade-strut joints performed [3,5,6]. Additionally, previous simulations have concentrated on evaluating loading characteristics at a single rotational rate [3–6]. Research extending numerical simulation models to investigate straight and helical-bladed turbines using models with all geometrical features including struts at multiple rotation rates will give greater insight into turbine characteristics, and allow for the evaluation of any advantages between the differing geometrical layouts.

In this current study, the blade loading of a straight and a helical vertical axis turbine was determined to characterise blade and strut loading. The hydrodynamic inputs were generated using DMS and CFD models, which were combined with the application of centrifugal and gravitational forces to form structural analysis models using beam theory and FEA. Characterization of maximum stresses and deflection levels and their relationships with blade azimuth angle were performed. This work also sought to determine whether straight or helical turbines are more suited to generate ocean power from both hydrodynamics and structural perspectives.

2. Turbine geometry

Two vertical axis turbine designs were simulated to evaluate the influence of variations of blade helicity on turbine structural loading characteristics. These models differed only in blade helicity as shown in Fig. 1, with all common geometrical dimensions outlined in Table 1. Only two designs were considered: a straight-bladed turbine, and a helical turbine with 15° of blade overlap. These were chosen as previous studies demonstrated that power output reduced significantly as blade overlap increased above 15° [2], reducing turbine utility for power generation. The geometrical layout of the straight-bladed turbine was based on an EFD turbine from literature to allow for validation of the numerical simulation techniques utilised [2,7]. The helical turbine used the same frontal area, strut geometry, blade chord, and blade section to allow comparisons between the two designs. Both turbines had two struts per blade located at the blade tips.

Table 1
Shared geometry of the straight and helical turbines.

Geometry	Dimensions
Number of blades	3
Turbine height	0.685 m
Blade section	NACA634021
Blade chord	0.065 m
Blade overlap	0°
Radius	0.457 m
Strut section	NACA0012
Strut chord	0.065 m
Number of struts per blade	2
Shaft diameter	0.048 m

3. Numerical simulation methods

Three loading simulation models were developed allowing for comparisons of the respective benefits of each numerical simulation technique. The simulation models were performed in two steps; first the hydrodynamics followed by the structural simulations. The models developed were the:

- DMS-Beam, DMS blade forces combined with a beam theory model;
- CFD-Beam, CFD blade forces combined with a beam theory model; and
- CFD-FEA, CFD model coupled to the FEA model using pressure mapping techniques.

3.1. Hydrodynamic simulations

Numerical simulations of the hydrodynamic forces were performed using DMS and CFD simulation models. For both models, force coefficients normal to the blade chord were determined, with the forces non-dimensionalised by dynamic pressure and blade chord. The CFD model was also used to output surface pressure data for use with the coupled CFD-FEA model.

3.1.1. Double multiple streamtube (DMS) model

The normal blade force coefficients were modelled using a DMS model previously developed by the authors based on the methods outlined in literature [9]. The turbine was modelled using a double actuator disk method to account for reductions in flow velocity through the streamtube from V_1 to V_2 as shown in Fig. 2, with no streamtube expansion modelled for simplicity. Using iterative methods upstream and downstream, induction factors were calculated from which blade angles of attack were determined. Once the latter were known, the forces normal to the blade chord were determined using lift and drag data obtained using the viscous airfoil analysis tool Xfoil [9]. As NACA634021 data was not readily available from literature at suitable Reynolds numbers, NACA634221 data was used as it was similar in profile, with a 2% difference in blade camber. The DMS model included dynamic stall modelling using the Gormont method to simulate the influence of the variations in blade angles of attack generated by the rotation of the blades [10]. Currently the DMS model developed by the authors cannot model helical turbines, as the hydrodynamic influence of the blade inclination has not been adequately accounted for.

3.1.2. Computational fluid dynamics (CFD) models

Turbine blade forces were simulated using transient time-accurate 3D CFD models using ANSYS CFX [11], which solved the incompressible fully turbulent URANS equations using an element-based finite volume method. All turbine models were meshed using unstructured tetrahedral elements using ANSYS CFX 13.0 [12–15]. Mesh resolution was set by specifying the mesh size and growth