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Influence of blade deformation and yawed inflow on performance of a horizontal axis tidal stream turbine

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A B S T R A C T

For a better design of tidal stream turbines operated in off-design conditions, analyses considering the effects of blade deformation and yawed inflow conditions are necessary. The flow load causes deformation of the blade, and the deformation affects the turbine performance in return. Also, a yawed inflow influences the performance of the turbine. As a validation study, a computational fluid dynamics (CFD) simulation was carried out to predict the performance of a horizontal axis tidal stream turbine (HATST) with rigid blades. The numerical uncertainty for the turbine performance with blade deformation and a yawed inflow was evaluated using the concept of the grid convergence index (GCI). A fluid−structure interaction (FSI) analysis was carried out to estimate the performance of a turbine with flexible composite blades, with the results then compared to those of an analysis with rigid blades. The influence of yawed inflow conditions on the turbine performance was investigated and found to be important in relation to power predictions in the design stages.

1. Introduction

In recent years, interest in renewable energy has been growing rapidly due to critical issues such as environmental pollution and high oil prices. Renewable energy, which comes from natural resources, can produce electricity with relatively less or even no pollution. Specifically, tidal stream energy is more predictable than other types of renewable energy, such as wind or wave energy. This type also produces less visual pollution and less acoustical noise than others types [1,2]. Thus, among the various sources of renewable energy, tidal stream energy has considerable potential for future electricity generation.

Besides studies for vertical axis tidal stream turbines [3], a large amount of research concerning numerical performance predictions of HATSTs has been carried out. Lee et al. [4] developed a boundary element momentum theory (BEMT) code and applied it to a HATST. The results of the performance prediction of a turbine using the BEMT code were similar to those of CFD around the design tip-speed ratio (TSR), though quite large differences were observed at lower TSRs. Batten et al. [5] presented cavitation tunnel experiments for a three-bladed HATST and compared the results with simulation results produced by BEMT. Mason–Jones et al. [6] predicted the performance of a HATST by means of a CFD analysis and performed a parametric study of the design variables. In addition, they defined a fitting function to consider a vertical velocity profile based on real sea data in the Bristol Channel and evaluated the effect of the vertical velocity profile on the turbine performance. Kinnas et al. [7] presented a numerical analysis of the performance of HATSTs based on a vortex lattice method (VLM). MacLeod et al. [2], Harrison et al. [8], and Lee et al. [9] studied the wake effect on the turbine performance using CFD. They presented the wake distribution of a HATST and evaluated the appropriate distance between adjacent turbines. Besides the general primitive variable-based formulation, McCombes et al. [10] presented a numerical model based on a vorticity-conserving form for the unsteady wake modeling of tidal stream turbines.

Many studies based on numerical analyses of HATSTs, including those by Song et al. [11] and others, were done with the assumption that the blade was sufficiently rigid and that the effects of blade deformation were negligible. However, a large chord-to-span ratio and a high-speed tidal current can cause the blades to be deformed

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Nomenclature

C	Chord length [m]	r	Refinement factor [-]
C_P	Power coefficient [-]	Re	Reynolds number [-]
C_{press}	Pressure coefficient [-]	T	Torque acting on the blades [$N \cdot m$]
e_a^{21}	Approximate relative error [-]	t	Local time for the rotating turbine [s]
e_{ext}^{21}	Extrapolated relative error [-]	T_0	Time for one revolution of the blade [s]
GCI_{fine}^{21}	Fine-grid convergence index [-]	TSR	Tip speed ratio [-]
h	Grid size [-]	U_∞	Free stream velocity [m/s]
P	Pressure [Pa]	ϕ	Computational solution variable for uncertainty assessment [-]
p	Estimated order of accuracy of the computational method [-]	ϕ_{ext}^{21}	Extrapolated value [-]
R	Radius of turbine [m]	ρ	Density [kg/m^3]
		ω	Vorticity [1/s]
		Ω	Rotational speed [rad/s]

[12]. Thus, performance prediction methods for HATSTs need to include FSI to reflect the effect of blade deformation. Nicholls–Lee et al. [12] developed an FSI simulation procedure for designing composite blades for HATSTs. They combined codes based on CFD and a finite element method (FEM) using a loose coupling method and applied the developed method to a three-bladed HATST with a diameter of 20 m.

In the research on wind turbines and marine propellers, the number of studies dealing with blade deformation is greater than those dealing with tidal stream turbines. Bazilevs et al. [13,14] developed a numerical method for analyzing the FSI of a wind turbine. They applied the method to a NREL 5 MW offshore wind turbine in full scale and discussed the effect of blade deformation. Kim et al. [15] developed a loose coupling method to consider the FSI of a wind turbine. They coupled aerodynamic, structural, and aero-acoustic analysis methods and evaluated the effects of blade deformation in terms of the power and noise performance. In addition, Young [16] presented an FSI analysis method, a boundary element method (BEM) combined with FEM, to predict the behavior of flexible composite marine propellers. In addition to the easier and more widely used loose coupling methods, there are methods involving strongly coupled CFD and FEM for FSI analyses. Strong coupling methods are more stable, compared to loose coupling methods, because they solve the fluid and structure fields simultaneously and suppress approximation errors and convergence problems due to the data transfer between the two fields [17].

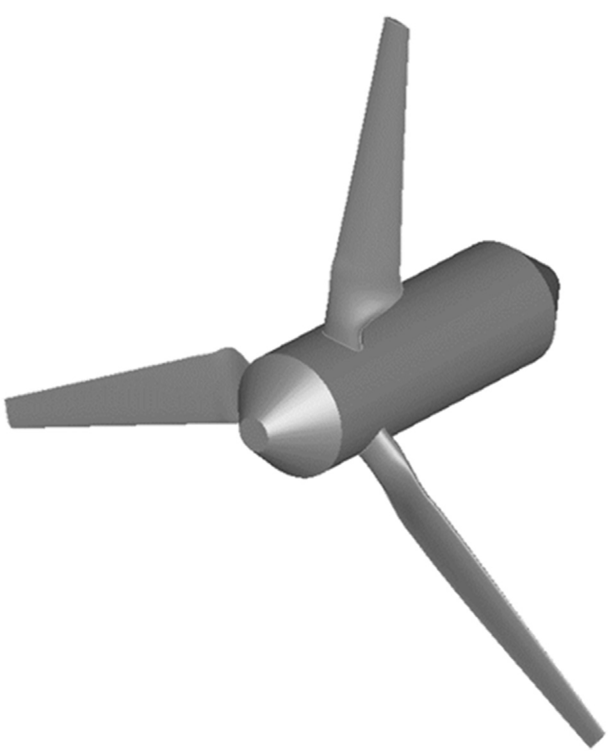

Fig. 1. Constructed baseline turbine.

Most studies of HATSTs have focused on analyzing performances with a uniformly straight inflow. However, the inflow angle of the tidal stream can vary depending on the time and site topography [18]. In other words, yawed inflow could occur in an actual sea environment and could seriously affect the performance of a turbine.

The present study focused on numerical predictions of the performance of a HATST considering the effects of blade deformation and a yawed inflow. The objectives are (1) to predict the performance of a HATST with rigid blades for validation, (2) to analyze the performance of a baseline turbine with deformed blades using a strong coupling method and compare to a case with rigid blades, and (3) to analyze the performance of a baseline turbine under yawed inflow conditions.

This paper is organized as follows. The physical problem is described first, and the computational method follows. The computational results are then presented and discussed. Finally, concluding remarks are made.

2. Problem description

As the baseline turbine, a three-bladed HATST with a diameter of 8 m was selected. The turbine blade was made of the NACA 63_3-418 foil section, which was used beyond the hub to the blade tip, i.e., between $r/R = 0.2$ to 1.0. Here, R denotes the radius of the turbine. A 2:1 elliptic root shape was adopted for connecting between the blade and hub.

To keep uniform lift generation throughout the span, the twist angles of airfoil section at various radial positions were designed to have the optimum angle of attack for each section. Chord lengths ranged from 0.68 m at the root to 0.27 m at the blade tip.

The axis of the twist of each section was at 0.25C away from the leading edge. Here, C is the chord length. For the hub fitting part, there was no twist angle and the center was located at 0.5C.

The design rotational speed, Ω, was 24.72 rpm. The operating speed expressed by the tip-speed ratio (TSR) was defined as