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A design tool and fabrication guidelines for small low cost horizontal axis hydrokinetic turbines

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ABSTRACT

Small scale and low cost hydrokinetic turbines can effectively contribute to solve energy deficits in developing countries, particularly in isolated communities, but some obstacles remain before they become a cost effective solution. This work reports on a methodology for designing and fabricating the main parts of small scale horizontal axis hydrokinetic turbines (HAHT) optimized for a specific site or operation conditions. A suitable software design tool, and low cost fabrication methods within reach and understanding of less developed communities are the basis of this methodology. A free and open source software package called Turbem developed by the authors allows a non-expert user to enter a minimum set of parameters and to obtain the complete optimal rotor geometry of the HAHT, with its estimated performance curves and maximum stresses. Turbem uses a combined approach of BEM theory and pseudo-gradient root finding for rotor optimal design, and classical solid mechanics for preliminary structural verification. The geometric information generated is sufficient for fabricating the rotor by a wide range of methods, ranging from hand carving up to CNC machining. In the latter case, Turbem generates CNC programs that are downloadable to any standard CNC machine, for direct fabrication of the blades and hub, or blade section templates as well. Hence, a technically sound rotor can be fabricated at a very low cost using wood as core and applying external layups of fiberglass with epoxy resin, as described herein. Using this methodology, small scale, cost effective HAHTs can be custom designed to take full advantage of specific site stream velocities and bathymetry. A 5 kW (nominal) hydrokinetic turbine was successfully designed, fabricated and field tested in order to validate and improve this methodology.

Introduction

Small scale, off grid and low cost energy, can become a feasible approach to solve energy problems in isolated communities throughout the planet (Kumar et al., 2009; Palit and Chaurey, 2011). In this context, hydrokinetic turbines could become an important contribution given the large amount of rivers and coast channels with appropriate bathymetry near small communities that could use such small scale, off grid and low cost electric power solutions (Anyi and Kirke, 2010, 2011; Ponta et al., 2010; Ponta and Dutt, 2000; Khan et al., 2007). In such cases, hydrokinetic energy has advantages over other off-grid technologies, with important social benefits, such as low energy distribution costs and providing local employment opportunities (Kumar et al., 2009). However, there still exist important technical barriers to overcome before reaching technical, economic and social feasibility.

Hydrokinetic ocean and river technologies are emerging fast, and they are estimated to reach a commercial stage at the mega-watt scale for tidal currents between 2015 and 2030 (Thresher, 2011). In addition, Anyi and Kirke (2010) concluded that non-ducted horizontal axis and low solidity hydrokinetic turbines are also likely to become a technically feasible solution in off grid small scale applications in the near future. However, the optimal design of a specific hydrokinetic turbine for a given site or operation conditions is a non-trivial task.

In order to reach economic feasibility, the design features must be such that the financial benefits of energy produced by the turbine, outweighs the initial investment and life time maintenance costs. Due to the wide range of bathymetry characteristics and water velocities available, the optimal hydrokinetic turbine is site-specific in order to maximize the power extraction. The Research and Development (R&D) cost of designing a new turbine is usually high, so a flexible design tool to minimize these costs for different size turbines is proposed and discussed in this paper.

This article focuses on the description of a new design tool and fabrication guidelines for reducing the investment cost (mainly design, materials, and manufacturing), in order to obtain a cost effective small scale open flow horizontal axis hydrokinetic turbine (HAHT). The objective of cost effectiveness can be explained as seeking to reach a solution that is an adequate balance between power output and operational reliability versus initial investment and operational costs. The Levelized Cost of Energy (LCOE) is used as a measure of cost-effectiveness and hence as

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Nomenclature

a	Axial induction factor
a'	Angular induction factor
α	Angle of attack [rad]
β	Inflow angle [rad]
c	Chord length [m]
C_D	Section drag coefficient
C_L	Section lift coefficient
C_p	Power coefficient
D	Rotor outer/tip diameter [m]
F	Tip and hub loss factors
F_A	Axial force [N]
H	Glauert's correction factor
θ	Twist angle [rad]
λ_r	Tip speed ratio
N_B	Number of blades
ρ	Fluid density [kg/m^3]
T	Torque on the rotor [Nm]
TSR	Tip speed ratio
V_∞	Free stream water velocity [m/s]
Ω	Angular velocity on the rotor [rad/s]

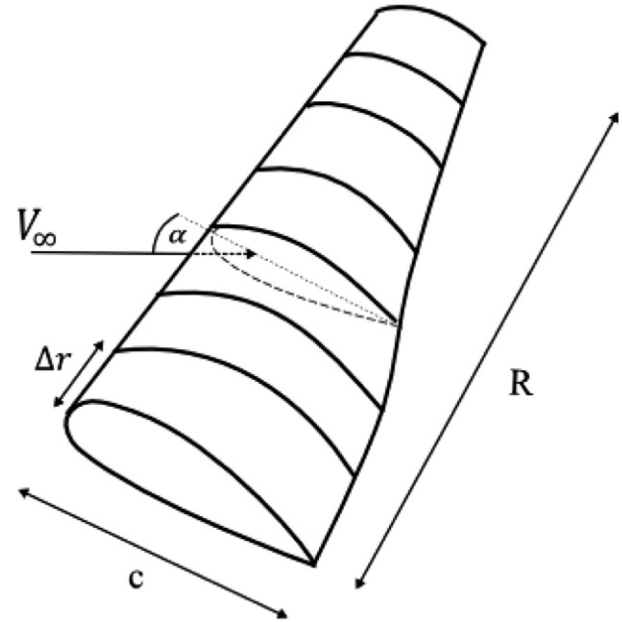

Fig. 2. The blades of the turbine are divided into two dimensional elements of height $\Delta \mathbf{r}$, cord length c, at a radius of r, and angle of attack of α. The total radius of the blade is R.

a way to systematically compare against other existing energy technologies. Given the small scale focus, in order to achieve economic and technical feasibility, the HAHT must be easy to design and fabricate. A free and open-source design and performance evaluation software called 'Turbem' was developed to facilitate the design process, lowering the initial development costs. Using Turbem along with appropriate materials and low cost fabrication methods as shown in this work, results in an easily replicable methodology to develop small scale HAHT. A 5 kW (nominal at 2 m/s of water velocity) HAHT was designed, built and tested (see Fig. 1) to validate this methodology. A video of the first field test is available at: https://www.youtube.com/watch?v=OLQCsgTfSB4.

Turbem

Although hydrokinetic turbines at the mega-watt scale are close to reach a commercial stage on its tidal application (Thresher, 2011), the design and fabrication methods are not readily available to small scale developers because of its technical complexity (Ponta et al., 2010). 'Turbine Blade Element Momentum' or 'Turbem' is a free and open-source software written in the C# (C sharp) programming language to obtain an optimal HAHT and to accurately predict its performance under different operating conditions. The software is available at: http://www.mecatronix.cl/?page_id=2277. This section describes the basic theoretical background behind Turbem and compares its main characteristics to other available turbine design software.

Fig. 1. 5 kW Horizontal axis hydrokinetic turbine designed with Turbem.

Theoretical background

The basic mathematical model behind Turbem software is the Blade Element Momentum theory (BEM), which is the most widely used theory for designing open flow turbomachinery (Tangler and Kocurek, 2004; Wilson et al., 1999). Because of its simplicity, BEM theory enables obtaining optimized turbines, with an acceptable accuracy and in a reasonable computing time.

To apply BEM theory each blade is divided into radial segments (see Figs. 2 and 3) so that the stream is subdivided into annular regions, where the angular momentum principle applies (Balme et al., 2007), and it is assumed that each annular region has no effect on the neighboring ones. This last assumption implies that the flow at each ring along the blades can be analyzed in 2D. Thus, torque and axial forces are estimated for each segment using both general momentum theory

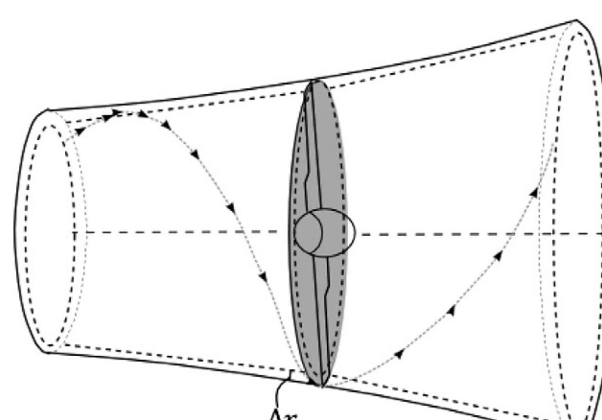

Fig. 3. Streamline of water flow passing through the rotor, at a theoretical annular disk of thickness "$\Delta \mathbf{r}$" and radius "r".