Energy for Sustainable Development 45 (2018) 142–149

Contents lists available at ScienceDirect

Energy for Sustainable Development

An approach for the optimization of diffuser-augmented hydrokinetic blades free of cavitation

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ARTICLE INFO

Article history:
Received 16 December 2017
Received in revised form 19 May 2018
Accepted 6 June 2018
Available online xxxx

Keywords:
Cavitation
Blade optimization
Hydrokinetic turbines
Diffuser
BET

ABSTRACT

Due to the Venturi effect caused by a diffuser, which speed-up the velocity through the rotor, shrouded turbines are able to exceed the Betz-Joukowsky limit if the power coefficient is based on the rotor diameter. However, on hydrokinetic turbines this increased velocity may also promote cavitation on the blade. As this subject is still not clear on the current literature, this work presents a novel approach for optimizing hydrokinetic turbines free of cavitation under diffuser effect. The model uses the minimum pressure coefficient as the criterion to keep the pressure near blade tip above water vapor pressure. It includes an extension of Vaz & Wood's optimization in order to take into account the influence of the diffuser speed-up ratio regarding cavitation effect. A changing on the thrust coefficient is assumed to optimize chord and twist angle distributions along the blade. As a result, the proposed model shows that cavitation is indeed sensitive to the diffuser speed-up ratio, demonstrating that such a phenomenon needs to be considered in the design of diffuser-augmented hydrokinetic turbines. Also, the optimization method corrects the chord without relevant changing in the turbine power coefficient, where the increased power output is about 42% higher than the bare turbine for a water velocity of 2.5 m/s. In this case, the model is assessed through comparisons using a 3-bladed hydrokinetic turbine with 10 m diameter, in which the diffuser speed-up ratio is varied. Furthermore, an evaluation is made with models available in the literature, suggesting good performance concerning the cavitation analysis on shrouded rotor design with the proposed optimization procedure.

Introduction

It is well known that the diffuser technology can increase the axial velocity through the rotor, improving the power output (Chen, Ponta, & Lago, 2011; Vaz & Wood, 2018). It means that a compact system can convert a greater amount of energy if the power coefficient is based on the rotor diameter (Sørensen, 2016). This advance has gained attention over the last decades as an alternative to conventional energy systems, especially on locations constrained by shallow waters or low stream velocity (Anyi & Kirke, 2010). As a consequence, some works in the current literature have reported the use of diffuser on hydrokinetic or tidal turbines (Belloni, Willden, & Houlsby, 2017; Dominguez, Achard, Zanette, & Corre, 2016; Silva et al., 2017). Among them, only a few takes into account the cavitation in order to design hydro blades. For example, recently Silva et al. (2017) developed an optimization approach based on Blade Element Theory (BET) for horizontal axis hydrokinetic turbines considering the possibility of cavitation, where the minimum pressure coefficient is the criterion used for identifying cavitation on blades. Their model has demonstrated good behavior, and indeed minimizes cavitation inception. But, it is applied only for bare hydrokinetic turbines. Batten, Bahaj, Molland, and Chaplin (2008) developed a BET model for hydrodynamic design of marine current turbines. In their model, the prediction of cavitation is carried out for certain cases with relatively shallow tip immersion. It is found that cavitation could be avoided with the use of suitable designs and choice of 2D sections. Even though their work presented very interesting thoughts on cavitation, studies on optimization of hydrokinetic blades free of cavitation are not done.

There is an extensive literature on diffuser-augmented turbines. But, most of them are related to wind rotors. Jafari and Kosasih (2014) performed a Computational Fluid Dynamics (CFD) study, in which the augmentation is heavily dependent on the diffuser geometry. They reported that a higher area ratio creates greater pressure reduction at the diffuser outlet, which increases the mass flow rate. Abe and Ohya (2004) combined a numerical and experimental investigation of a shrouded turbine with a flanged diffuser technology.

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https://doi.org/10.1016/j.esd.2018.06.002
0973-0826/

They found that the turbine thrust coefficient using diffuser is smaller than for a bare wind turbine. Ohya and Karasudani (2010) developed a turbine within a diffuser shroud with a broad-ring brim at the exit. The shrouded wind turbine power is increased by a factor between 2 and 5 over a bare wind turbine in the same operating condition. It shows the importance of the development of models able to optimize shrouded hydrokinetic blades free of cavitation. Rio Vaz, Mesquita, Vaz, Blanco, and Pinho (2014) developed important formulations for the performance analysis of wind turbine with diffuser based on BET. Their results yielded good agreement with experimental data. Based in their work, Vaz and Wood (2016) stated the equations for the aerodynamic optimization of a wind turbine with diffuser. In this case, it is assumed that the same conditions for the axial velocity in the wake of an ordinary wind turbine can be applied on the flow far downwind of the diffuser outlet, as proposed by van Bussel (1999).

Therefore, as the authors are unaware of any study of blade optimization free of cavitation under diffuser effect, an optimization procedure for shrouded hydrokinetic blades is proposed in this work. The methodology is an extension of Vaz and Wood (2016) optimization, where the minimum pressure coefficient criterion is incorporated into the turbine thrust coefficient in order to keep the pressure near blade tip above water vapor pressure. The chord of the blade is determined using a one-dimensional analysis, where a correction to avoid cavitation is employed. A hydrokinetic turbine with 10 m diameter is used to evaluate the effect of the diffuser speed-up ratio concerning the cavitation. To assess the proposed approach, comparisons with other models available in the literature are made. As a result, the model shows that cavitation is sensitive to the diffuser speed-up ratio, suggesting that such a phenomenon needs to be considered in the design of shrouded hydrokinetic turbines. In addition, the optimization method corrects the chord without relevant changing in the turbine power coefficient. Also, the shrouded turbine power output increases about 42% when compared with the bare turbine for a water velocity of 2.5 m/s.

The remainder of this paper is organized as follows. The next section shows the Cavitation criterion used in the model. Section 3 presents the mathematical modeling for the Optimum design of diffuser-augmented hydrokinetic blades, in which a simple one-dimensional axial momentum theory with a diffuser is carried out. This section also shows the expressions for the changing in the thrust coefficient, which leads to a corrected formulation of the chord distribution free of cavitation. In Section 4, the Results and discussion are stated, where the performance and comparisons of the proposed model is presented. Section 5 shows the Conclusions of this study.

Cavitation criterion

According to Adhikari, Vaz, and Wood (2016), cavitation effect typically occurs in hydro turbines, usually leading to vibration, blade surface damage and performance loss. Therefore, those issues need to be avoided in hydro rotors. Hence, as the diffuser increases the flow axial velocity at the rotor plane, it is necessary to include a restriction to avoid cavitation in the design of hydrokinetic blades. The most used criterion to minimize or avoid cavitation on hydro turbines relates the number of cavitation (σ) with the minimum pressure coefficient ($C_{p\,\min}$) through the expression

$$C_{p\,\min} + \sigma \geq 0, \tag{1}$$

where $C_{p\,\min}$ is the minimum value of the pressure coefficient C_p, defined by

$$C_p = \frac{p - p_{atm}}{\frac{1}{2}\rho W^2}, \tag{2}$$

ρ is the density, p and p_{atm} are the local and atmospheric pressures respectively, and the relative velocity of water on each blade section is defined by Vaz and Wood (2016) as

$$W = \sqrt{[\gamma V_0(1-a)]^2 + [\Omega r(1+a')]^2}. \tag{3}$$

The parameter γ is the diffuser speed-up ratio, and it is responsible for modifying the axial velocity on the rotor. The free-stream velocity corresponds to V_0. The parameters a and a' are the axial and tangential induction factors, respectively, while Ω and r are the angular velocity and radial position of the turbine. The formulation for the number of cavitation σ is (Shinomiya, 2015)

$$\sigma = \frac{p_{atm} + \rho g H - p_v}{\frac{1}{2}\rho W^2}, \tag{4}$$

where g is the gravitational acceleration, H is the submerged distance and p_v is the vapor pressure. Substituting Eq. (4) in Eq. (1), it gets $V_{CAV} \geq W$, where the cavitation velocity is

$$V_{CAV} = \sqrt{\frac{p_{atm} + \rho g H - p_v}{-\frac{1}{2}\rho C_{p\,\min}}}. \tag{5}$$

Note that the cavitation can be avoided whether the relative velocity on each blade section is lower than the local cavitation velocity. This condition is fundamental for the optimization methodology described below in which the chord length is corrected at each section when $V_{CAV} < W$. Fig. 1 illustrates the static pressure condition on a DAHT blade section. In this case, the rotor is located near the inlet of the diffuser.

Optimum design of diffuser-augmented hydrokinetic blades

The optimum expressions for shrouded turbines come from the momentum equations with rotational velocities in the flow (Fletcher, 1981; Philipis, 2003; Sørensen, 2016). According to Rio Vaz et al. (2014) for modern turbines it is necessary to consider the effect of the tangential induction factor, a'. The elemental torque can be obtained directly from the momentum equation applied to the control surface shown in Fig. 2, in which the infinitesimal area at the

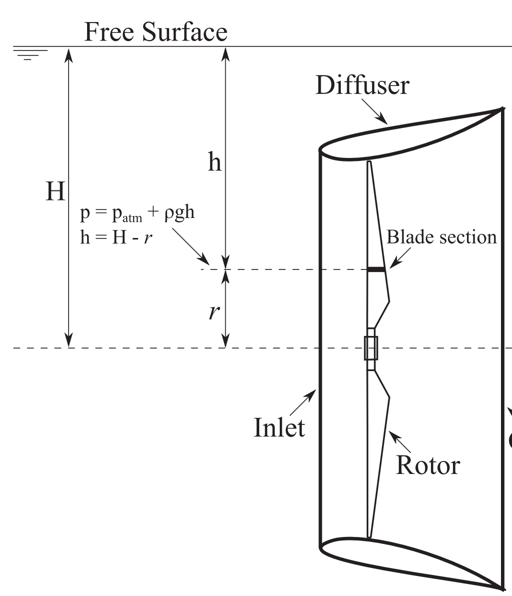

Fig. 1. Simplified illustration of the static pressure condition on a DAHT blade section.