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Mixed CFD-1D wind turbine diffuser design optimization

F. Sorribes-Palmer*, A. Sanz-Andres, L. Ayuso, R. Sant, S. Franchini

IDR/UPM, E.T.S.I. Aeronáutica y del Espacio, Universidad Politécnica de Madrid, Pza. Cardenal Cisneros, 3, 28040 Madrid, Spain

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ABSTRACT

A method to design a diffuser augmented wind turbine (DAWT) is proposed, using as a guiding point the optimal pressure drop at the turbine. The use of concepts and expressions derived from a 1D analytic model helped to reduce the number of computational fluid dynamics simulations needed to find the optimal configuration. The proposed configuration can extract energy from the flow with the same efficiency as the state-of-the-art shrouded wind turbine (SWT) configurations but generating a significantly smaller wake, which makes this configuration a good candidate for wind farms or tidal applications. Furthermore, as a product of the 1D model, universal curves for the power coefficient have been obtained, as a function of the thrust coefficient, or disk loading, which have been compared with numerical and experimental results, showing a good agreement. Finally, the maximum ideal power coefficient has been found for a given configuration, which helps to estimate the margin for improvement of an actual design.

1. Introduction

In the last years, electricity generation costs have been decreasing, and in the best wind farms locations wind energy technologies are already competitive with regard to conventional power generation technologies Blanco [1], Neij [2], Goudarzi and Zhu [3]. In this context of rapid technological changes, wind farms become soon obsolete, providing an incentive to replace the existing wind farms soon by more efficient ones. Repowering a wind farm is the process of replacing existing wind turbines with new turbines that either have a larger nameplate capacity or more efficiency, resulting in a net increase of power generation [4].

Energy extraction from low wind energy density flows, as it can be in urban sites, has also lead the wind turbine industry to develop configurations to adapt to different environments, improve efficiency, and reduce costs [5]. Thus, different concepts have been developed to enhance efficiency of wind turbines in regions with less wind energy density. One of the approaches to increase the efficiency that has been devised is the diffuser augmented wind turbine (DAWT), which increases both the mass flow through the rotor section and the trust coefficient [6]. This concept has been explored by a remarkable number of researchers [7–10]. The theoretical performance enhancements of these devices are only achieved when the duct is sufficiently aligned with the wind, and the flow is no too gusty. This drawback, and other aerodynamic phenomena related to wind turbines, is studied by Sørensen [11], where different models to predict aerodynamic forces, design of rotor-blade airfoils, analysis of wind farms, and wind turbine wake simulations, are also considered.

One important point concerning shrouded wind turbines is the size of the wake, which can give rise to wake interference, which can cause fatigue loading of downwind turbines and also reduce the efficiency of wind farms. These are some of the reasons why wind turbine wake structure has been studied extensively [11–13].

Turbines installed inside small shrouded inlets are also used to deliver power to wireless sensors in pipes and ducts as shown in Howey et al. [14]. In this paper, the design of a turbine of 3.2 cm outer diameter that delivers between 80 μW and 2.5 mW of electrical power at an air speed in the 3–7 m /s range is presented.

Another approach is the so-called wind-lenses or shrouded wind turbine (SWT), which use a large flange attached at the exit of the diffuser shroud, thus increasing the low pressure region behind the rotor, due to the strong vortex wake formation behind the flange. This region helps to drawn a huge amount of mass flow inside the shrouded diffuser, thus accelerating the flow passing through the rotor. The flow around flanged diffusers has been studied experimentally and numerically by several researchers [15–18].

Concerning the diffuser, as a result of their numerical simulations and wind tunnel experiments, optimal open angles between

* Corresponding author.
E-mail address: felix.sorribes@upm.es (F. Sorribes-Palmer).

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Nomenclature

Acronyms

CFD	computational fluid dynamics
DAWT	diffuser augmented wind turbine
SWT	shrouded wind turbine

Greek symbols

δ	perturbation of c_{pex} around c_{pex0}, slope of c_{pex} (K_{pc})
ΔK_{pc}	perturbation of K_{pc} around $K_{pc\ max0}$
Δp_c	total pressure loss at the turbine section
Δp_d	total pressure loss at the diffuser
μ	diffuser expansion area ratio A_{ex} /A_c

Roman symbols

A_c	turbine cross-section area
A_{ex}	diffuser exit cross-section area
$A_{\infty l}$	capture area limit
C_T	thrust coefficient
C_{Wc}	extracted power coefficient referred to the turbine section area A_c (same as C_P)
C_{Wex}	extracted power coefficient referred to the exit cross section area A_{ex}
c_{pex}	pressure coefficient at the diffuser exit section
K	net total pressure loss coefficient, referred to the exit speed
K_{pc}	total pressure loss coefficient in the turbine, referred to the exit speed
k_{pc}	total pressure loss coefficient in the turbine, referred to the turbine section speed (disk loading)
K_{pd}	total pressure loss coefficient in the duct, referred to the exit speed
k_{pd}	total pressure loss coefficient in the duct, referred to the turbine section speed
p_{ex}	static pressure at the diffuser exit
p_∞	static pressure of the undisturbed flow upstream
Q	volumetric flow
r_{CT}	thrust coefficient ratio
r_K	total pressure loss coefficient ratio, disk loading ratio
Re	Reynolds number
r_{Wc}	augmentation ratio, referred to Betz limit
U_c	flow speed at the turbine section
U_{ex}	flow speed at the exit section
U_∞	flow speed upstream
W_c	power extracted from the flow by a turbine

Subscripts

Betz	Betz limit
c	turbine section
ex	diffuser exit section
i	ideal
max	maximum value
r	real
0	case $\delta = 0$

10° and 12° are suggested in Chaker et al. [18] for flow at Reynolds number of 66500 (referred to the diffuser inlet section), for an empty diffuser and for a diffuser shrouding a small wind turbine, respectively. For larger half cone angles (included angles), a recirculation zone appears at the diffuser inner wall due to boundary layer separation, leading to large pressure losses in the diffuser.

Shrouded wind turbine flow fields are examined by Aranake et al. [19] who investigated several points: regions with flow separation, the development of velocity profiles, and the interaction between the turbine wake and shroud boundary layer, including the sensitivity of the solutions to blade rotation rate.

The possibility of using a shrouded diffuser with a curved flange at the exit in a vehicle is explored both numerically and experimentally by Chang et al. [20], reaching a factor of wind speed acceleration of 2.1 and a power output 3 times the one of the bare wind turbine. A similar diffuser augmented tidal turbine (DATT) is studied by simulation and validated with experiments by Shi et al. [21] for the propulsion of an autonomous underwater vehicle, doubling the power coefficient of the turbine without diffuser, achieving a maximum power coefficient of 0.83 with an optimal diffuser.

The impact of the diffuser augmentation on the performance of a tidal stream turbine under yawed flows is studied by Cresswell et al. [22]. The design allows the turbine performance to be maintained up to ± 30° yaw angles. One of the conclusions of this work is that diffuser augmented turbines are less well suited to array deployment than are bare rotors, unless additional measures are taken to reduce wake interference or promote wake mixing. This conclusion points out the relevance of reducing turbine wake cross-section in order to reduce the distance between these devices in the case of considering their use to implement a wind farm.

The design of a duct and a rotor of a current streamlined marine turbine to optimize the efficiency over the largest operating range is carried out by Luquet et al. [23]. Two coupled generators are considered, which can rotate around a vertical axis fixed on the seafloor to get orientated with the flow. Different duct concepts are analyzed numerically; the maximum flow acceleration factor of the current velocity achieved is 1.4. The numerical models of the two more relevant duct shapes are validate with experimental tests.

A numerical investigation on different shrouded wind turbines approaches, flanged and double diffusers with double cone shape splitter, is presented in Kannan et al. [24]. The turbine achieves a 61% wind speed velocity increase over a 4 m/s free stream velocity using a diffuser of 16° included angle, coupled with a 4° splitter opening angle.

Flow separation in a diffuser, also called diffuser stall, is one of the main problems concerning power extraction. It depends on several parameters: diffuser inlet conditions, exit conditions, Reynolds number, Mach number, and diffuser geometry, as compiled in Blevins [25]. In this handbook, diffuser stall is studied for different configurations: two-dimensional, conical, annular, straight-walled, and curved wall diffusers. Curves for different stall regimes (first appreciable, large transitory, fully developed, hysteresis zone, and jet flow) for different diffusers as a function of geometry parameters are presented. Also the design principles followed in literature for two-dimensional diffusers with short vanes are summarized.

A multi-element diffuser is analyzed by Hjort and Larsen [26,27], employing a passive boundary-layer stall control, which exceeds the Betz limit by 50%. Besides energy augmentation, the diffuser helps shield the aero-acoustic noise propagation, and provides visual encapsulation of the rotating rotor. Design of a low tip-speed-ratio rotor for a new multi-element DAWT will lead to a very silent application.

The vortex shedding in a flanged diffuser, as the one proposed