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On the Effect of the Tip Clearance on the Aerodynamic and Aeroacoustics of a Diffuser-Augmented Wind Turbine

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A computational study of two Diffuser-Augmented Wind Turbines (DAWTs) is carried out to investigate both the hydrodynamic flow field and the far-field noise. The two configurations differ for the tip-clearance ratio, defined as the ratio between the tip clearance and the rotor radius. The DonQi[®] wind turbine, a three blades ducted rotor, is adopted as baseline configuration because of the availability of reference data. It has a tip-clearance ratio of 2.5%. The second configuration is obtained from the first one by elongating the rotor radius such to force the interaction between the turbulent boundary layer, developing over the suction side of the diffuser, and the tip of the blades, thus resulting in a tip-clearance ratio of 0.7%. The rotor with the longer blades shows a reduction of the thrust coefficient because of the lower lift generated by the diffuser that results in a lower axial velocity at the rotor plane. It is shown that this is caused by the smaller tip gap that forces the break down of the rotor tip vortex in smaller turbulent structures immediately after the rotor plane and that induces earlier flow separation along the suction side of the diffuser. The tip-clearance ratio has also a strong effect on the far-field noise. For angles between 60° and 120°, where 0° corresponds to the axial upstream direction, the blade tonal noise, at frequency equal to the blade passing frequency and higher harmonics, is the dominant source. For other angular directions, noise increase is found for the smaller tip-clearance ratio case associated to an additional noise source, that becomes dominant, linked to an increase of the energy content of velocity fluctuations in the gap region. This noise source, that can be modeled as a monopole source located in the gap, causes an increase of broadband noise at frequencies higher than the third blade passing frequency and a tonal peak at a frequency equal to 4.5 times the blade passing frequency and higher harmonics.

I. Introduction

Wind energy is emerging as a reliable resource for power production. In 2016, it contributed to cover 10.4% of the overall electricity demand [1] and it is expected to grow up to 29.6% in 2030 [2]. Most of the wind energy production is obtained from on-shore wind turbines with rated power in the range of 500 kW to 3-4 MW. The spread of on-shore wind energy is limited by the stringent regulations against visual and acoustic pollution. For this reason, off-shore wind turbines are often used but the larger distance with respect to the final user and the cost of the infrastructure affect negatively the final cost of energy.

A possible solution to increase the energy produced on-shore is to use small urban wind turbines, which can be located within populated areas with minor visual and acoustic effects with respect to large wind turbines. However, in urban areas, the presence of buildings increases the surface roughness which results in lower wind speed, thus limiting the energy production. To overcome this problem, Diffuser-Augmented Wind Turbines (DAWTs) represent an interesting concept. They are realized by embedding a rotor within a diffuser (also named duct or shroud) that increases the wind speed at the rotor location. Von Betz [3] was the first to propose this solution to increase the rated power. The validity of this assumption was experimentally verified later [4, 5]. Despite the efforts, there are still many contradictory opinions about the maximum power coefficient that can be achieved using DAWTs. This is mainly due to the fact that it is not easy to decouple the rotor from the duct [6].

The first analytical model, based on one-dimensional theory, was the one proposed by de Vries [7] who found that the maximum achievable power coefficient is 0.7698. Afterwards, Hansen et al. [8] derived a momentum theory where the wake mixing was neglected. They showed that the Betz limit can be exceeded up to 0.94. Similarly, van Bussel [9] derived a momentum theory for a DAWT showing that power augmentation up to 2.5 can be achieved with respect to the

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isolated rotor when a large back pressure is obtained. Additionally, he showed that the optimal rotor thrust coefficient is equal to 8/9. A similar result was also obtained by Jamieson [10] and Werle et al. [11]. Khamlaj and Rumpfkeil [12] studied the assumptions behind the analytical models of van Bussel, Jamieson and Werle finding that their are valid only for short duct. More recently, de Oliveira et al. [13] studied the interaction between a body and an actuator disk where a stationary vortex ring was used to model an axisymmetric shroud. No other assumption on the shape of the duct was made. They confirmed that embedding an actuator disk within a duct alters the power coefficient and that the interaction affects the actuator loading at which the optimal power coefficient is reached. As a consequence, the coupling of a rotor with optimal thrust coefficient with a duct might result in a non-optimal ducted wind turbine [14, 15]. The discussed analytical models are based on the assumption of an uniformly loaded actuator disk, which is not representative of realistic rotors. For this purpose, Bontempo and Manna [16] proposed a semi-analytical model for a non-uniformly loaded ducted actuator disk, which accounts for the non-linear mutual interaction between the duct and the rotor.

Despite the extensive literature on analytical models, no complete experimental or computational benchmark dataset is available. Goal of this manuscript is to describe in details the flow through a realistic DAWT. Since performing experiments on a full-scale DAWT is challenging and it is difficult to equip the blades with multiple sensors to obtain the loading distribution along the radius of the blades, a computational approach is chosen. For this reason, the DonQi[®] wind turbine has been selected because of the availability of reference data and of the geometry. As a matter of fact, Tang et al. [15] performed experimental measurements embedding a uniformly loaded perforated disk into the duct and Dighe et al. [14] carried out two-dimensional RANS simulation of the same configuration. The outcome of this research represents the first available dataset on a realistic wind turbine that can be used by other researchers to validate analytical and semi-analytical models. Since DAWTs are installed close to urban areas, they are subject to noise regulations, which can be a further limitation to their commercial success, an aeroacoustics study is performed. More in details, the effect of the tip-clearance ratio is investigated because of its relevance for ducted systems [17]. The flow is computed by solving the explicit, transient, compressible lattice-Boltzmann (LB) equation, while the acoustic field is obtained by means of the Ffowcs Williams and Hawkings [18] (FWH) acoustic analogy.

The manuscript is organized as follows. First the computational solver and the computational set-up are described. Then, the hydrodynamic flow field and the far-field noise are discussed. Finally, the relevant results are summarized in the conclusions.

II. Computational method

A. Flow solver

The lattice-Boltzmann method is used to compute the flow field because it was shown to be accurate and efficient for noise prediction in presence of complex flow problems [19–21]. The commercial software 3DS Simulia PowerFLOW 5.5a is used. The software solves the discrete LB equation for a finite number of directions. For a detailed description of the method, the reader can refer to Succi [22] and Shan et al. [23], while to Chen and Doolen [24] for a review. The LB method determines the macroscopic flow variables starting from the mesoscopic kinetic equation, i.e. the LB equation. The discretization used for this particular application consists of 19 discrete velocities in three dimensions (D3Q19), involving a third-order truncation of the Chapman-Enskog expansion. It was shown that this scheme accurately approximates the Navier-Stokes equations for a perfect gas at low Mach number in isothermal conditions [25]. The distribution of particles is solved by means of the LB equation on a Cartesian mesh, known as a lattice. An explicit time integration and a collision model are used. The LB equation can then be written as:

$$g_i(\mathbf{x} + \mathbf{c}_i \Delta t, t + \Delta t) - g_i(\mathbf{x}, t) = C_i(\mathbf{x}, t), \quad (1)$$

where g_i is the particle distribution function along the i -th lattice direction. It statistically describes the particle motion at a position x with a discrete velocity $\mathbf{c}_i$ in the i -th direction at time t . $\mathbf{c}_i \Delta t$ and Δt are space and time increments, respectively. $C_i(\mathbf{x}, t)$ is the collision term for which the formulation based on a unique Galilean invariant [26] is used. The equilibrium distribution g_i^{eq} of Maxwell-Boltzmann, conventionally used for small Mach number flows, is adopted [25].

A Very Large Eddy Simulation (VLES) model is implemented to take into account the effect of the sub-grid unresolved scales of turbulence. Following Yakhot and Orszag [27], a two-equations $k - \epsilon$ Renormalization Group (RNG) is used to compute a turbulent relaxation time that is added to the viscous relaxation time:

$$\tau_{\text{eff}} = \tau + C_\mu \frac{k^2/\epsilon}{(1 + \eta^2)^{1/2}}, \quad (2)$$

where $C_\mu = 0.09$ and η are a combination of the local strain, local vorticity and local helicity parameters. The term η allows to mitigate the sub-grid scale viscosity in the presence of large resolved vortical structures.

In order to reduce the computational cost, a pressure-gradient-extended wall-model (PGE-WM) is used to approximate the no-slip boundary condition on solid walls [28, 29]. The model is based on the extension of the generalized law-of-the-wall model [30] to take into account the effect of pressure gradient. The expression of the PGE-WM is:

$$u^+ = \frac{1}{\kappa} \ln \left(\frac{y^+}{A} \right) + B \quad (3)$$

where

$$B = 5.0, \quad \kappa = 0.41, \quad y^+ = \frac{u_\tau y}{\nu}, \quad (4)$$

and where A is a function of the pressure gradient. It captures the physical consequence that the velocity profile slows down and so expands, due to the presence of the pressure gradient, at least at the early stage of the development. The expression of A is:

$$A = 1 + \frac{f | \frac{dp}{ds} |}{\tau_w}, \quad \hat{\mathbf{u}}_s \cdot \frac{dp}{ds} > 0 \quad (5)$$

$$A = 1, \quad \text{otherwise.} \quad (6)$$

In the equations, τ_w is the wall shear stress, dp/ds is the stream-wise pressure gradient, $\hat{\mathbf{u}}_s$ is the unit vector of the local slip velocity and f is a length scale equal to the size the unresolved near-wall region. These equations are iteratively solved from the first cell close to the wall in order to specify the boundary conditions of the turbulence model. For this purpose, a slip algorithm [24], obtained as generalization of a bounce-back and specular reflection process, is used.

B. Noise computation

The compressible and time-dependent nature of the transient Computational Fluid Dynamics (CFD) solution together with the low dissipation and dispersion properties of the LB scheme [31] allow extracting the sound pressure field directly in the near-field up to a cut-off frequency corresponding to approximately 15 voxels per acoustic wavelength.

In the far field, noise is computed by using the FWH equation [18]. The formulation 1A, developed by Farassat [32] and extended to a convective wave equation is used in this study [31, 33]. The formulation is implemented in the time domain using a source-time dominant algorithm [34]. Integrations are performed on the surface of the model where the unsteady pressure is recorded with the highest frequency rate available on the finest mesh resolution level (referred to as solid formulation). As a consequence, acoustic monopoles and dipoles distributed on the surface of the DAWT are the only source terms of interest [35] and the non-linear contribution related to the turbulent fluctuations in the wake of the DAWT are neglected.

III. Computational set-up

The DonQi[®] DAWT, shown in figure 1, is used in this manuscript as reference. It consists of a diffuser and a three-blades rotor. The diffuser is obtained as axisymmetric revolution of an airfoil cross section, as designed by NLR. The diffuser has diameter equal to $D_{in} = 1.74$ m at the inlet, $D_{th} = 1.54$ m at the throat, $D_{out} = 2.0$ m at the exit, a chord equal to $c_{diff} = 1$ m. The radius of the rotor is $R_0 = 0.75$ m, corresponding to a tip-clearance (TC) ratio of 2.5%, defined as the ratio between the tip clearance and the rotor radius. The rotor has three blades with a NACA 2207 aerofoil, which chord length varies from 130 mm at the root to 105 mm at the tip. The twist angle ranges from 40.5° at the root to 0.3° at the tip. The chord (c_b) and twist angle (ϕ) distribution along the blade radius are plotted in figure 2. The blades are connected to a hub (upstream) and a nacelle (downstream). The hub is composed of a cylinder, with diameter and length equal to 125 mm and 100 mm, and an upstream aerodynamically shaped geometry. The latter is

Fig. 1 Front view of the DonQi® wind turbine geometry.

Fig. 2 Radial distribution of the rotor blade chord and twist angle.

obtained through the rotation of a quarter of an ellipsis with minor axis equal to 100 mm and major axis equal to 125 mm. Similarly, the nacelle has the cylinder length equal to 75 mm and the ellipsis major axis equal to 100 mm.

To study the effect of the tip clearance on the aerodynamic and aeroacoustic performance, a second DAWT is investigated. It is obtained from the reference DonQi® DAWT by extending the final part of the blade up to a tip-clearance ratio of 0.7%. The value of the tip clearance is chosen such that the tip of the blade is submerged in the turbulent boundary layer convecting over the suction side of the diffuser.

For both configurations, the free-stream velocity is set at $U_\infty = 5$ m/s, which is a characteristic value for urban wind turbines, corresponding to a free-stream Mach number and a Reynolds number based on the diffuser chord equal to 0.015 and 3.31×10^5 . The rotational speed is $\omega = 39.84$ rad/s, corresponding to a tip-speed ratio $\lambda = \omega R_0 / U_\infty = 6$, which was found to be optimal in a previous study [36].

Boundary layer transition is forced both on the diffuser and the blades with a zig-zag strip. For the diffuser, an annular zig-zag strip is placed at 10% of the diffuser chord at the suction side (i.e., the inner part of the duct); it has length, height and λ_z (i.e., tip-to-tip distance) respectively equal to 1.5 mm, 2.5 mm and 4 mm. For the blades, the zig-zag strip extends from 15% to 99% of R_0 and it has length, height and λ_z respectively equal to 0.5 mm, 1.25 mm and 4 mm.

The origin of the reference frame is located at the blades' center of revolution (figure 1). The x -axis is directed along the center-line of the diffuser and is positive in the streamwise direction; the y -axis is oriented in the wall-normal direction and the z -axis is such to have a left-hand oriented reference system.

The simulation domain is a box of length equal to $23 c_{diff}$ in the streamwise direction, and $26 c_{diff}$ in the $y-z$ plane. The rotor plane is placed $9 c_{diff}$ downstream of the inlet. Free-stream inlet boundary conditions are applied at $x = -9 c_{diff}$ while pressure outlet boundary conditions are applied at $x = 14 c_{diff}$. Slip boundary conditions are applied at the other walls. A total of 11 mesh refinement regions, named as VR, with resolution factor equal to 2 are employed. They are detailed in figure 3 only near the DAWT where regions with the same resolution are displayed

Fig. 3 Volume resolution (VR) region distribution near the DonQi® wind turbine geometry.

Fig. 4 Surface y^+ distribution. (left) front and (right) back view.

with the same color. The region with the highest resolution is the offset around the zig-zag trip, where the voxel size is 4.167×10^{-1} m, corresponding to 2400 voxel per diffuser chord. This results in a distribution of y^+ as shown in figure 4 for the finest resolution case investigated. In total, approximately 284 million voxels and 52 million of surfels are used to discretize the problem. A mesh resolution study has been carried out in order to verify the time and grid convergence of the computations. The accuracy of the discretization is also validated comparing the computational results with experimental data. Details are described in section IV. The flow-simulation time is 1.42 seconds (9 rotor revolutions) requiring 7200 CPU hours per revolution on a Linux Xeon E5-2690 2.9 GHz platform.

The physical time step, corresponding to a Courant-Friedrichs-Lewy (CFL) number of 1 in the finest mesh resolution level, is 7.27×10^{-7} s. The unsteady pressure on the surface of the DonQi® wind turbine is sampled with a frequency of 10 kHz ($St_{c_{diff}} = f c_{diff} / U_\infty = 2000$) for a physical time of 1 s (equals to 6 rotor revolution).

IV. Grid resolution study

Grid resolution study is carried out to verify that the solution is not dependent on the computational grid. Three grid resolutions are investigated corresponding to the smallest voxel size equal to 1200 (coarse), 1800 (medium) and 2400 (fine) voxels per diffuser chord. This is achieved by proportionally increasing the resolution of each refinement region. The corresponding number of fine equivalent voxels N for the three configurations is 1.46×10^6 , 2.67×10^6 and 4.33×10^6 .

The blade thrust coefficient C_t and the diffuser aerodynamic force coefficient C_F are used for the convergence analysis. They are defined as:

$$C_t = \frac{T}{\frac{1}{2} \rho U_\infty^2 A_{rot}}, \quad (7)$$

$$C_F = \frac{F}{\frac{1}{2} \rho U_\infty^2 A_{rot}}, \quad (8)$$

Fig. 5 (left) Rotor thrust coefficient C_t and (right) total aerodynamic force coefficient generated by the duct C_F versus the number of equivalent fine voxels N .

where T is the thrust, i.e. the axial force, generated by the wind turbine, F is the total aerodynamic force generated by the duct and A_{rot} is the rotor area equal to πR_0^2 , where R_0 varies with the configuration.

Results of the convergence study are shown in figure 5 for both configurations. For the smaller TC configuration, the convergence study is carried out only for the medium and fine cases because of the grid dependent result found for the baseline case. The inspection of the figures shows that convergence is reached for both hydrodynamic quantities with maximum variation between the medium and fine cases lower than 4% and 1% for the C_t and C_F , respectively. When compared with experimental results, for a similar configuration but without forced transition, good agreement is found. As a matter of fact, Dighe et al. [14] reported a value of C_t equal to 0.81 using the same duct geometry and a porous disc to mimic the isolated rotor.

The figures further show that, reducing the TC from 2.5% to 0.7%, the C_t of the blades reduces. This is due to the lower velocity at the rotor plane induced by the lift generated by the diffuser.

The dependence of the C_t on the TC shall be considered as a guideline for the design of DAWT. As a matter of fact, DAWT are equipped with acoustic liners like perforated surface in correspondence of the rotor plane to dampen the rotor tonal noise. This surface can alter the development of the boundary layer triggering transition or altering the boundary layer thickness at the rotor plane. This causes the reduction of thrust discussed before in addition to noise increase as will be shown in section VI.

V. Hydrodynamic flow field

Visualizations of the instantaneous flow field around the baseline DonQi[®] DAWT (TC = 2.5%) and the one with longer blade (TC = 0.7%) are shown in figure 6. Iso-surfaces of the λ_2 criterion [37] color contoured with the velocity magnitude are plotted. For both cases, the flow accelerates, because of the lift force generated by the diffuser, reaching higher streamwise velocity at the rotor plane with respect to the free-stream one. The velocity increase is visible from the color contour and it is better quantified in figures 7 and 8. In the former, contours of the instantaneous streamwise velocity in the center line $x - y$ plane are displayed; in the latter, the time-averaged streamwise velocity u in the axial direction is plotted for different radial locations. Here the errorbar indicates the root mean square of u .

Large differences are found comparing the two cases. Starting from the instantaneous flow visualization of the baseline configuration, it is evident that laminar tip vortices are present. These vortices convect, following a helicoidal path, become unstable and transition to turbulent flow structures. Lignarolo et al. [38] showed that, for a tip vortex, the pairing instability is the precursor mechanism for the vortex distortion and break down. For the current configuration, the tip vortex moves away from the duct surface and no other interaction is present downstream. This is better visualized in figure 7 where the development of the tip vortex in the near wake of the rotor is shown. Since the tip vortex is generated at the rotor plane, where the diameter of the duct is minimum, a shear region is formed which induces the formation of a secondary coherent vortex near the tip of the blade as visible from the three-dimensional flow organization. This vortex is characterized by similar velocity magnitude as the tip vortex but it is less strong and, for the magnitude of λ_2 selected for the figure, it is not visible anymore in the near wake.

Fig. 6 Instantaneous flow field around the DonQi® DAWT with TC = 2.5% (left) and TC = 0.7% (right). Iso-surface of the λ_2 criterion color contoured with the velocity magnitude.

Fig. 7 Time-averaged streamwise velocity u in the axial direction at different radial locations for the TC = 2.5% (left) and TC = 0.7% (right).

Fig. 8 Time-averaged streamwise velocity u in the axial direction at different radial locations for the TC = 2.5% (left) and TC = 0.7% (right).

Fig. 9 Time-averaged pressure coefficient C_p along the chord of the diffuser.

The smaller TC configuration, figure 6 (right), shows both the tip vortex and the secondary vortex. While the latter has similar features for the two investigated configurations, the former, because of the close proximity to the surface and the consequent stronger shear, breaks immediately in smaller turbulent structures convecting with lower velocity magnitude with respect to the baseline case. The effect of the interaction results in lower flow acceleration and lower streamwise velocity at the rotor plane at $r/R_0 = 1$ of approximately 13% with respect to the baseline case (figure 8). This is caused by the lower lift generated by the diffuser because of the interaction between the turbulent layer and the tip vortex that alters the natural development of the flow over the diffuser suction side. Because of the interaction, the turbulent boundary layer over the diffuser suction side separates at approximately 70% of the diffuser chord.

The interaction and the boundary layer separation affect the pressure coefficient C_p distribution over the diffuser as shown in figure 9 where the time-averaged C_p is plotted. The C_p curve for the smaller clearance configuration is embedded into the one of the baseline case. This suggests that, for the same airfoil angle of attack, the airflow sees a thinner airfoil that generates less lift and lower mass flow rate through the duct [13]. In addition, the plateau in the C_p distribution starting from 70% of the diffuser chord agrees with the flow separation visible from the instantaneous flow organization.

The interaction between the blade and the turbulent boundary layer is better illustrated in figure 10 where three slices with iso-contours of the time-averaged vorticity magnitude, computed in the body-fixed reference frame, and the time-averaged surface pressure are shown for the two configurations. The three slices are located in front, at the mid plane and behind the blade.

Fig. 10 Time-averaged vorticity magnitude and time-averaged surface pressure near the tip of the blade for the TC = 2.5% (left) and TC = 0.7% (right).

Fig. 11 Overall Sound Pressure Level (OASPL) obtained from an arc of 10 equally spaced microphones located at $2R_0$ from the center of the rotor.

For the shorter blade, in the gap, a region with higher vorticity is visible. This corresponds to the tip vortex generated at the edge of the blade. The tip vortex weakly interacts with the turbulent boundary layer as shown by the region of low vorticity that separates the vortex from the boundary layer. The tip vortex grows in strength moving downstream and is clearly visible in the near wake, i.e. the region of high vorticity magnitude. Its presence breaks the symmetry of the near wake, which shows a distortion that results in the formation of the additional vortex described in figure 6. The tip vortex has also an effect on the time-averaged surface pressure. A region of lower pressure with respect to the static free-stream pressure is present below the blade due to the fact that the vortex moves momentum away from the surface. Conversely, for the smaller TC, the blade interacts with the turbulent boundary layer, thus resulting in a region of higher time-averaged pressure in front of the blade. The low pressure region is also stronger and develops up to the trailing edge of the blade. This means that the tip vortex is constrained in the tip-gap region and does not lift up as it happens for the reference configuration. This is also visible from the time-averaged surface pressure where no low pressure region is present for the longer blade. The near wake flow shows a less strong vortex and a weaker deformation of the blade's wake. However, the high vorticity region is broader and a secondary peak is present. This is due to the break up of the laminar tip vortex into smaller structures as discussed earlier.

VI. Far-field noise

The effect of the TC on the acoustic behavior of the DAWT is investigated in this section. The far-field noise is computed using the FWH acoustic analogy as discussed in section IIB. Far-field data are obtained on a circular array of equally spaced microphones placed at $2R_0$ from the center of the duct. Two circular arrays, one in the $x - y$ plane and one in the $x - z$ plane, are used with 36 microphones per arc. The angular spacing between the microphones is 10° . In the figure, 0° corresponds to the upstream axial direction.

Figure 11 shows the Overall Sound Pressure Level (OASPL) in a cross plane. It is expressed in dB with reference pressure equal to 20×10^{-5} Pa. Results are integrated from 2 Hz to 392.4 Hz, i.e. up to 20 times the Blade Passing Frequency (BPF). Because of the symmetric nature of the acoustic field, results from the four arcs are averaged. The

Fig. 12 Sound Power Level (PWL) versus the Blade Passing Frequency (BPF) obtained from integration from the four arcs of microphones located at $2R_0$ from the center of the rotor.

Fig. 13 Power Spectral Density (PSD) versus the Blade Passing Frequency (BPF), for three microphones located at 30° , 90° and 120° and radial distance equal to $2R_0$.

figure shows that reducing the TC an increase in noise, up to 10 dB and 5 dB respectively downstream and upstream of the DAWT, is found without variation of the directivity pattern. In the range between 60° and 120° , no variation between the two cases is found. In this range, the directivity pattern is oriented upstream with a relative maximum at 70° . Both directivity patterns are different from the one expected for an isolated wind turbine where a shadow region is expected at about 90° . This might be due to the presence of the duct that alters the conventional direction of noise propagation.

To better describe the acoustic field, Sound Power Level (PWL) versus the BPF is reported in figure 12. PWL is obtained integrating the data from the spherical distribution of microphones and it is expressed in dB. It shows that the rotor is the dominant source of noise. For both configurations the first two BPFs have the same power intensity. The power associated with the first BPF is approximately 20 dB larger than the second. At frequencies higher than the second BPF the two curves diverge; the configuration with smaller TC shows larger broadband noise with amplitude larger than the tonal peak corresponding to the third BPF of the larger TC case. For this configuration an additional tonal peak arises at a frequency equal to 4.5 BPF and its harmonics that cannot be associated to the rotor noise. The physical nature of this source of noise can be associated to an increase of the turbulent velocity fluctuations because of the smaller TC. A similar phenomenon was observed for fan noise by Fukano and Jang [17]. They found that noise increases by decreasing the mass flow rate, by increasing the TC and that it is relevant for frequencies lower than the fourth BPF. Conversely, for the DAWT, it is found that this source of noise dominates at frequencies higher than the fourth BPF and that it appears when reducing the TC. The opposite trend for DAWT can be due to the different working principles of the two systems.

The physical mechanisms behind this source of noise are further investigated by plotting the Power Spectral Density (PSD) versus the BPF, expressed in dB/Hz, for three microphones located at 30° , 90° and 120° and radial distance equal to $2R_0$ in figure 13. It confirms that the tone associated with the second noise source is dominant in the upstream and downstream directions where its intensity is comparable or higher than the ones of the first two BPFs. More interesting, the energy associated with this source of noise is similar for the three directions, suggesting that it might be modeled as

Fig. 14 Band-pass filtered time derivative of the pressure field for central frequency corresponding to the first blade passing frequency (top) and 4.5 times the blade passing frequency (bottom). The TC = 2.5% case is displayed on the left while the TC = 0.7% case on the right.

Fig. 15 Band-pass filtered time derivative of the streamwise velocity component for central frequency equal to 4.5 times the blade passing frequency. The TC = 2.5% case is displayed on the left while the TC = 0.7% case on the right.

Fig. 16 Spectra of the streamwise velocity component Φ_{uu} at two point in front and behind the tip gap region.

a monopole source of sound in the gap.

The previous observations are further supported by the band-pass filtered time derivative of the pressure field in figure 14. The figures correspond to central frequency equal to the first BPF (top) and 4.5 times the BPF (bottom). The baseline case is represented on the left while the shorter tip clearance configuration on the right. The first row confirms that for both cases noise is generated by the rotor. Conversely, the second row shows that for the shorter tip clearance, an additional source of noise can be localized in the tip gap region with intensity comparable to the one of the first BPF. This source of noise is mainly oriented in the axial location and weakly affect noise between 60° and 90° as discussed before. Despite the presence of large vortical structures in the wake, no additional noise source is detected.

As stated before, for fan applications, this source of noise is associated to an increase of the velocity fluctuations in the tip gap region. The effect of the amplification of the velocity fluctuations is shown in figure 15. Here the band-pass filtered streamwise velocity component for central frequency equal to 4.5 times the BPF is displayed. The baseline case is represented on the left while the shorter tip clearance configuration on the right. The figure shows a different pattern of the turbulent flow structures near the blade. Comparing the two configurations, it is evident that, for the shorter tip clearance configuration, the near wake of the tip show higher energy content in this frequency band while both configurations show a similar spatial distribution of the velocity fluctuations. An additional relevant difference, that can be linked to the flow separation shown in figure 9, is the stronger surface vortex interaction visible only for the smaller TC configuration.

To better assess that the increase of the velocity fluctuations is the main physical mechanism associated to the noise increase at frequencies higher than the third BPF, the spectra of the streamwise velocity component Φ_{uu} are plotted in figure 16. Here spectra at two locations, upstream ($x/R_0 = -0.13$, $y/R_0 = 1.0$) and downstream ($x/R_0 = 0.13$, $y/R_0 = 1.04$) of the blades are plotted. The figure shows that the turbulent fluctuations increase behind the blade and that, for the shorter TC case, an increase with respect to the baseline case, is present at frequency higher than the third BPF in agreement with the acoustic results (figures 12 and 13). An additional small peak is measured at a frequency equal to 4.5 times the BPF which might be linked to the observed tonal noise at this frequency.

VII. Conclusions

The effect of the tip-clearance ratio for a Diffuser-Augmented Wind Turbine (DAWT) on both the hydrodynamic flow field and the far-field noise is investigated with a computational approach. Lattice-Boltzmann Very-Large-Eddy Simulations are used. Two DAWT configurations are investigated. They differ for the tip-clearance ratio, defined as the ratio between the tip clearance and the rotor radius. The DonQi[®] wind turbine, a three blades ducted rotor, is adopted as baseline configuration because of the availability of few reference data. It has a tip clearance ratio of 2.5%. The second configuration is obtained from the first one by elongating the rotor radius such to force the interaction between the turbulent boundary layer developing over the suction side of the diffuser and the tip of the blades, thus resulting in a tip-clearance ratio of 0.7%. The rotational speed is $\omega = 39.84$ rad/s, corresponding to a tip-speed ratio $\lambda = \omega R_0 / U_\infty = 6$, which was found to be optimal in a previous study [36], where $U_\infty = 5$ m/s is the free-stream velocity. Boundary layer transition is forced on the diffuser suction side and the blades to mimic more realistic flow conditions and the presence of the turbulent flow induced by the liner usually installed to dampen the tonal noise generated by the rotor.

Comparing the two configurations, it is found that the rotor with the longer blades shows a reduction of the rotor thrust coefficient because of the lower lift generated by the diffuser that results in a lower axial velocity at the rotor plane up to 13% with respect to the baseline case. Three-dimensional flow visualizations through the λ_2 criterion and contour of the instantaneous streamwise velocity component show that this is caused by the smaller tip gap that forces the break down of the rotor tip vortex in smaller turbulent structures immediately after the rotor plane and that induces earlier flow separation along the suction side of the diffuser. Conversely, for the shorter blade configuration, the tip vortex convects almost undisturbed in the duct following a helicoidal path and transition to turbulence because of the vortex pairing instability mechanism [38]. The distribution of the pressure coefficient along the duct surface, for the longer blades, is embedded within the one with larger tip clearance showing that, because of the interaction, a thinner airfoil is seen by the incoming flow. For the longer blade, a local maximum in the surface pressure is found in correspondence of the leading edge of the tip section due to the flow deceleration induced by the interaction.

The tip clearance ratio has also a strong effect on the far-field noise showing up to 10 dB increase in the axial direction downstream of the rotor. For angles between 60° and 120°, where 0° corresponds to the axial upstream direction, the blade tonal noise, at frequency equal to the blade passing frequency and higher harmonics, is the dominant source. For other angular directions, noise increase is found for the smaller tip-clearance ratio case. This is associated to an additional noise source due to an increase of the energy content of velocity fluctuations in the gap region. Spectra of the velocity fluctuations show that the increase of the turbulent fluctuations is present only downstream of the rotor plane. This noise source has the same intensity in all the directions and can be modeled as a monopole source located in the gap. It causes an increase of broadband noise at frequencies higher than the third blade passing frequency and a tonal peak at a frequency equal to 4.5 times the blade passing frequency and higher harmonics.

References

- [1] Pineda, I., and Tardieu, P., “Wind in power 2016 European statistics,” Tech. rep., Wind Europe, 2017.
- [2] Tardieu, P., “Wind energy in Europe: Scenarios for 2030,” Tech. rep., 2017.
- [3] von Betz, A., “Energieumsetzungen in Venturidusen,” *Die Naturwissenschaften*, Vol. 10, 1929, pp. 160–164.
- [4] Lilley, G., and Rainbird, W., “A Preliminary Report on the Design and Performance of Ducted Windmills,” Tech. rep., College of Aeronautics, 1956.
- [5] Gilbert, B., and Foreman, K., “Experimental demonstration of the diffuser-augmented wind turbine concept,” *Journal of Energy*, Vol. 3, No. 4, 1979, pp. 235–240. doi:10.2514/3.48002.

- [6] Dighe, V., Avallone, F., Tang, J., and van Bussel, G., "Effects of gurney flap on the performance of diffuser augmented wind turbines," *35th Wind Energy Symposium*, 2017, 2017.
- [7] de Vries, O., "Fluid Dynamic Aspects of Wind Energy Conversion," Tech. rep., 1979.
- [8] Hansen, M., Sørensen, N., and Flay, R., "Effect of Placing a Diffuser around a Wind Turbine," *Wind Energy*, Vol. 3, No. 4, 2000, pp. 207–213. doi:10.1002/we.37.
- [9] van Bussel, G., "The science of making more torque from wind: Diffuser experiments and theory revisited," *Journal of Physics: Conference Series*, Vol. 75, No. 1, 2007, p. 012010. doi:10.1088/1742-6596/75/1/012010.
- [10] Jamieson, P., "Generalized limits for energy extraction in a linear constant velocity flow field," *Wind Energy*, Vol. 11, No. 5, 2008, pp. 445–457. doi:10.1002/we.268.
- [11] Werle, M., and Presz, W., "Ducted Wind/Water Turbines and Propellers Revisited," *Journal of Propulsion and Power*, Vol. 24, No. 5, 2008, pp. 1146–1150. doi:10.2514/1.37134.
- [12] Khamlaj, T., and Rumpfkeil, M., "Theoretical Analysis of Shrouded Horizontal Axis Wind Turbines," *Energies*, Vol. 10, No. 12, 2017, p. 38. doi:10.3390/en10010038.
- [13] De Oliveira, G., Pereira, R., Ragni, D., Avallone, F., and Van Bussel, G., "How does the presence of a body affect the performance of an actuator disk ?" *Journal of Physics: Conference Series*, Vol. 753, No. 2, 2016. doi:10.1088/1742-6596/753/2/022005.
- [14] Dighe, V., Avallone, F., and van Bussel, G., "Computational study of diffuser augmented wind turbine using actuator disc force method," *International Journal of Computational Methods and Experimental Measurements*, Vol. 4, No. 4, 2016, pp. 522–531. doi:10.2495/CMEM-V4-N4-522-531.
- [15] Tang, J., Avallone, F., and van Bussel, G., "Experimental study of flow field of an aerofoil shaped diffuser with a porous screen simulating the rotor," *International Journal of Computational Methods and Experimental Measurements*, Vol. 4, No. 4, 2016, pp. 502–512. doi:10.2495/CMEM-V4-N4-502-512.
- [16] Bontempo, R., and Manna, M., "Solution of the flow over a non-uniform heavily loaded ducted actuator disk," *J. Fluid Mech.*, Vol. 728, 2013, pp. 163–195. doi:10.1017/jfm.2013.257.
- [17] Fukano, T., and Jang, C.-M., "Tip clearance noise of axial flow fans operating at design and off-design condition," *Journal of Sound and Vibration*, Vol. 275, No. 3-5, 2004, pp. 1027–1050. doi:10.1016/S0022-460X(03)00815-0.
- [18] Ffwoes Williams, J., and Hawkings, D., "Sound Generation by Turbulence and Surfaces in Arbitrary Motion," *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, Vol. 264, No. 1151, 1969. doi:10.1098/rsta.1969.0031.
- [19] Khorrami, M., Fares, E., and Casalino, D., "Towards Full Aircraft Airframe Noise Prediction: Lattice Boltzmann Simulations," *20th AIAA/CEAS Aeroacoustics Conference*, American Institute of Aeronautics and Astronautics, Atlanta, Georgia, 2014, pp. AIAA 2014–2481. doi:10.2514/6.2014-2481.
- [20] Casalino, D., Hazir, A., and Mann, A., "Turbofan Broadband Noise Prediction Using the Lattice Boltzmann Method," *AIAA Journal*, 2017, pp. 1–20. doi:10.2514/1.J055674.
- [21] Avallone, F., Van Der Velden, W., Ragni, D., and Casalino, D., "Noise reduction mechanisms of sawtooth and combed-sawtooth trailing-edge serrations," *Journal of Fluid Mechanics*, Vol. 848, 2018. doi:10.1017/jfm.2018.377.
- [22] Succi, S., *The lattice Boltzmann equation for fluid dynamics and beyond*, 1st ed., Clarendon Press, Oxford, 2001.
- [23] Shan, X., Yuan, X.-F., and Chen, H., "Kinetic theory representation of hydrodynamics: a way beyond the Navier–Stokes equation," *Journal of Fluid Mechanics*, Vol. 550, 2006, pp. 413–441. doi:10.1017/S0022112005008153.
- [24] Chen, S., and Doolen, G., "Lattice Boltzmann method for fluid flows," *Annual Review of Fluid Mechanics*, Vol. 30, No. 1, 1998, pp. 329–364. doi:10.1146/annurev.fluid.30.1.329.
- [25] Chen, H., Chen, S., and Matthaeus, W., "Recovery of the Navier-Stokes equations using a lattice-gas Boltzmann method," *Physical Review A*, Vol. 45, No. 8, 1992, pp. R5339–R5342. doi:10.1103/PhysRevA.45.R5339.
- [26] Chen, H., Zhang, R., and Gopalakrishnan, P., "Lattice Boltzmann Collision Operators Enforcing Isotropy and Galilean Invariance," , aug 2015.

- [27] Yakhot, V., and Orszag, S., "Renormalization group analysis of turbulence. I. Basic theory," *Journal of Scientific Computing*, Vol. 1, No. 1, 1986, pp. 3–51. doi:10.1007/BF01061452.
- [28] Teixeira, C., "Incorporating Turbulence Models into the Lattice-Boltzmann Method," *International Journal of Modern Physics C*, Vol. 09, No. 08, 1998, pp. 1159–1175. doi:10.1142/S0129183198001060.
- [29] Wilcox, D., *Turbulence modelling for CFD (Third Edition)*, DCW Industries, Incorporated, 2006.
- [30] Launder, B., and Spalding, D., "The numerical computation of turbulent flows," *Computer Methods in Applied Mechanics and Engineering*, Vol. 3, No. 2, 1974, pp. 269–289. doi:10.1016/0045-7825(74)90029-2.
- [31] Brès, G., Pérot, F., and Freed, D., "A Ffowcs Williams - Hawkings Solver for Lattice-Boltzmann Based Computational Aeroacoustics," *16th AIAA/CEAS Aeroacoustics Conference*, American Institute of Aeronautics and Astronautics, Stockholm, Sweden, 2010, pp. AIAA 2010–3711. doi:10.2514/6.2010-3711.
- [32] Farassat, F., and Succi, G., "A review of propeller discrete frequency noise prediction technology with emphasis on two current methods for time domain calculations," *Journal of Sound and Vibration*, Vol. 71, No. 3, 1980, pp. 399–419. doi:10.1016/0022-460X(80)90422-8.
- [33] Najafi-Yazdi, A., Bres, G., and Mongeau, L., "An acoustic analogy formulation for moving sources in uniformly moving media," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, Vol. 467, No. 2125, 2010, pp. 144–165. doi:10.1098/rspa.2010.0172.
- [34] Casalino, D., "An advanced time approach for acoustic analogy predictions," *Journal of Sound and Vibration*, Vol. 261, No. 4, 2003, pp. 583–612. doi:10.1016/S0022-460X(02)00986-0.
- [35] Curle, N., "The Influence of Solid Boundaries upon Aerodynamic Sound," *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, Vol. 231, No. 1187, 1955, pp. 505–514.
- [36] van Dorst, F., "An improved design for a diffuser augmented wind turbine," Ph.D. thesis, Delft University of Technology, 2011.
- [37] Jeong, J., and Hussain, F., "On the identification of a vortex," *Journal of Fluid Mechanics*, Vol. 285, 1995, p. 69. doi:10.1017/S0022112095000462.
- [38] Lignarolo, L., Ragni, D., Scarano, F., Simão Ferreira, C., and van Bussel, G., "Tip-vortex instability and turbulent mixing in wind-turbine wakes," *Journal of Fluid Mechanics*, Vol. 781, 2015, pp. 467–493. doi:10.1017/jfm.2015.470.