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Design of a boundary-layer suction system for turbulent trailing-edge noise reduction of wind turbines

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The present work introduces a method for the design of a boundary-layer suction system for turbulent trailing-edge noise reduction of wind turbines. Since the latter hitherto has been primarily assessed in a two-dimensional framework, the paper is meant to point out whether the predicted improvements carry over to wind turbine flow. Since the processes of trailing-edge noise reduction and effective power alteration are intimately bound together, great emphasis is put on an accurate prediction of pump power requirement, the latter being based on a detailed suction hardware system implying pressure losses across each component. An exemplarily performed design reveals that, within a certain design regime, trailing-edge noise reduction is accompanied by an enhancement of rotor power. However, as of a distinct cross-over point at which the pump power requirement exactly compensates the amelioration of aerodynamic power, a trade-off between aeroacoustics and aerodynamics arises. The method bases on fully-resolved URANS computations and is applied to the generic NREL 5 MW turbine.

1. Introduction

A permanently growing environmental burden as well as vanishing resources of fossil energy constitute wind energy (besides other important forms of renewable clean energy, such as thermoelectrics [1,2] and photovoltaics [3]) to be a major pillar of the proclaimed energy transition. The pursue of onshore wind energy expansion is inevitably accompanied by both larger turbine dimensions as well as decreasing distances to inhabited areas and, hence, increasing noise exposure. The composition of total wind turbine noise emission unites various different sources, within which TBL-TEN has proven to be the main contributor waiving high levels of inflow turbulence [4]. Since the intensity of TBL-TEN is directly linked with (the fifth power of) the flow velocity and, hence, aerodynamic rotor power, its reduction plays an important role in regard to rotor design [5]. There are two distinct ways to reduce TBL-TEN: passive and active (energy-fed) methods.

Passive methods are targeted at both the source of TBL-TEN, i.e. the induction of wall pressure fluctuations due to turbulence as well as its mechanism of scattering at the trailing-edge. Whereas the former approach finds expression in specifically shaping the airfoil [6], the latter implies the use of porous surfaces or trailing-edge add-ons like serrations or brushes [7–9]. However, potential improvements through passive methods are counterbalanced by diverse factors. With their design being tailored to a certain flow condition, passive methods oftentimes lose effectiveness when facing flow conditions deviant from the design point [5]. In addition, the reduction of the primary noise source may be accompanied by the introduction of one or more other noise sources [8]. Third, besides the obtained aeroacoustic improvements, passive methods may imply a deterioration of aerodynamic performance and, hence, introduce a trade-off between aerodynamics and aeroacoustics, further demanding innovative approaches to mitigate flow-induced wind turbine noise [10].

Active methods directly affect the emergence of wall pressure fluctuations and, in turn, the noise-guiding boundary-layer state at the trailing-edge. Their linkage to energy supply allows the adaption to a wide range of flow states. Whereas a lot of research effort is directed to TBL-TEN reduction through passive methods (an overview is provided in Ref. [5]), far less is present in regard to the active counterpart [11–13]. Extensive research at the Institute of Aerodynamics and Gas Dynamics (IAG) experimentally and numerically revealed the impressive potential of distributed boundary-layer suction to reduce TBL-TEN, manifesting in an achieved reduction of up to 5.5 dB for a NACA 64418 airfoil [14–18]. However, the method has primarily been assessed in a

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Nomenclature

c_d	Drag coefficient
c_l	Lift coefficient
$\overline{D}$	Directivity function
$\Delta\tilde{p}$	$\frac{\Delta p}{1/2\rho_\infty U_\infty^2}$, non-dimensional pressure difference
Δl_{cd}	Collector duct offset
$\Delta L_{p,design}$	Relative difference of target design sound pressure level to baseline maximum
$\Delta L_{p,discret}$	Discretization of design space into target design states
Δp_{bubble}	Pressure drop across the separation bubble at hole entrance
$\dot{m}$	Mass flow
$\overline{v'v'}$	Reynold stress component in wall-normal direction
$\tilde{D}_{cd}$	Non-dimensional collector duct diameter
$\tilde{r}_{c_q}$	Ratio of non-dimensional mass flow rate over a single chamber
$\tilde{r}_p$	Ratio of non-dimensional pressure difference across perforated skin over a single chamber width
$\tilde{v}_b$	Non-dimensional discharging velocity
$\tilde{x}_{c,beg/end}$	Suction chamber geometry variables
$\tilde{x}_{cd,beg}$	Collector duct geometry variable
A	Area
b	Segment width
c	Chord length
c_0	Speed of sound
c_Q	$\frac{\iint \rho_s U_s dxdy}{\rho_\infty U_\infty cb}$, non-dimensional suction mass flow rate (3D)
c_q	$\frac{\int \rho_s U_s dx}{\rho_\infty U_\infty c}$, non-dimensional suction mass flow rate (2D)
D	Rotor diameter, Hole diameter
D_h	Hydraulic diameter
H	Hub height
h	Duct height, enthalpy
k, $\mathbf{k}$	Wave number, wave number vector
k_D	Scaling factor for hole diameter due to roughness ($k_D \leq 1$)
k_{por}	Scaling factor for the plate porosity due to blocked holes ($k_{por} \leq 1$)
L	Wetted airfoil length
L_p	Sound pressure level
l_{trans}	Transitional length
$M_{(c)}$	(Convection) Mach number
P	Power, wave number frequency spectrum of wall pressure fluctuations
p	(Static) pressure
POR	porosity
R	Blade span, Noise source to observer distance
r	Radial blade distance
$r_{b,start/limit}$	Starting and border position of blowing region
r_{pump}	Radial position of pump
Re	Reynolds number
Re_{eff}	Effective Reynolds number of hole flow
S	Far-field noise spectrum
T	Absolute static temperature
t	(Plate, Airfoil) thickness
U	(Streamwise) velocity, Peripheral force
U_c	Mean convective velocity of wall pressure fluctuations
V	Cross-sectionally averaged flow velocity
x	Streamwise coordinate axis
y	Wall-normal coordinate axis
z	Spanwise coordinate axis

Subscripts

0	Stagnation condition
1	Hole entrance station
2	Hole exit station
∞	Freestream
b	Blowing
c	Chamber
cd	Collector duct
ex	Aft of pump
in	Before pump
s	Suction, surface

Symbols

α	Angle of attack
Δ	Relative difference between suction and baseline configuration, $\Delta X = X_s - X_{base}$
η_{pump}	Pump efficiency
γ	Specific heat ratio
λ	Friction factor
Λ_y	Integral length scale of $\overline{v'v'}$ separation in vertical direction
$\mathcal{O}$	Observer position
μ	Absolute viscosity
ω	Angular frequency
Φ	Geometric angle between z-axis and origin-observer connecting line in the yz-plane
ϕ_m	Moving-axis spectrum
Ψ	Rotor azimuth angle
$\Re$	Ideal gas constant ($p = \rho\Re T$)
ρ	Density
τ	Observer azimuth angle
Θ	Spatial angle between the x-axis and origin-observer connecting line
$\tilde{\phi}_{yy}$	Spectral decomposition of vertical Reynolds stress $\overline{v'v'}$

two-dimensional framework, not hitherto taken into account complex flow phenomena as associated with wind turbines. There is still no general guidance available for the transfer of the proclaimed potential to full-size wind turbines and prove about the results in a three-dimensional environment is still pending.

The aim of the present study is to provide insight into the performance and realisation of a practical suction system for a generic wind turbine since the application of suction and blowing through the airfoil surface is likely to be considered complex and impractical [5]. It reports on the development of a method for the design of a boundary-layer suction system for TBL-TEN reduction of wind turbines and is meant to point out whether the predicted improvements owing to boundary-layer suction in the two-dimensional regime carry over to full-size wind turbine flow. An exemplary design is performed providing insight into the individual design steps addressed to both noise as well as power-related performance of the suction system. Great emphasis is put on an accurate prediction of pump power requirement, the latter being based on a detailed suction hardware design involving pressure losses across each component. Since combining free