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Numerical and experimental investigation of a beveled trailing-edge flow field and noise emission

W.C.P. van der Velden [a],*, S. Pröbsting [a], A.H. van Zuijlen [a], A.T. de Jong [a], Y. Guan [b], S.C. Morris [b]

[a] Delft University of Technology, Kluyverweg 2, 2629 HT Delft, The Netherlands
[b] University of Notre Dame, IN 46556, United States

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ABSTRACT

Efficient tools and methodology for the prediction of trailing-edge noise experience substantial interest within the wind turbine industry. In recent years, the Lattice Boltzmann Method has received increased attention for providing such an efficient alternative for the numerical solution of complex flow problems. Based on the fully explicit, transient, compressible solution of the Lattice Boltzmann Equation in combination with a Ffowcs-Williams and Hawking aeroacoustic analogy, an estimation of the acoustic radiation in the far field is obtained. To validate this methodology for the prediction of trailing-edge noise, the flow around a flat plate with an asymmetric 25° beveled trailing edge and obtuse corner in a low Mach number flow is analyzed. Flow field dynamics are compared to data obtained experimentally from Particle Image Velocimetry and Hot Wire Anemometry, and compare favorably in terms of mean velocity field and turbulent fluctuations. Moreover, the characteristics of the unsteady surface pressure, which are closely related to the acoustic emission, show good agreement between simulation and experiment. Finally, the prediction of the radiated sound is compared to the results obtained from acoustic phased array measurements in combination with a beamforming methodology. Vortex shedding results in a strong narrowband component centered at a constant Strouhal number in the acoustic spectrum. At higher frequency, a good agreement between simulation and experiment for the broadband noise component is obtained and a typical cardioid-like directivity is recovered.

1. Introduction

The trailing-edge noise of a wind turbine blade is currently one of the most dominant noise sources on a wind turbine and, therefore, understanding and modeling of the physics associated with the generation and propagation of noise are of paramount importance for the design of silent wind turbines [1]. Brooks et al. [2] defined the fundamental airfoil self-noise mechanisms associated with the trailing edge, such as the noise produced by the transitional or turbulent boundary layer flow with the trailing edge or that due to vortex shedding. In the case of the interaction between the boundary layer flow and the trailing edge, perturbations of the unsteady surface pressure field, introduced and convected with the turbulent eddies, are scattered at the discontinuity posed by the trailing edge. The acoustic radiation depends largely on the length

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* Corresponding author.
E-mail address: W.C.P.vanderVelden@TUDelft.nl (W.C.P. van der Velden).

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Nomenclature

a	speed of sound
b	width of computational domain, model span
B	law of the wall constant
c_i	discrete velocity vector
C_μ	subgrid scale model constant
C_i	Bhatnagar–Gross–Krook collision term
d	height of tripping device
f	frequency
$f_\#$	focal ratio
g_i	displacement vector of the distributed particles
h	thickness of flat plate
H	shape factor
l	model chord
l_z	spanwise correlation length
L_i	acoustic pressure loading term
M	Mach number vector
p	pressure
q	dynamic pressure
r	geometric observer distance
R	radius of curvature
Re	Reynolds number
St	Strouhal number
t	time
T	temperature
u_i	velocity vector
V	velocity magnitude, $V=\sqrt{u_x^2+u_y^2}$
x_i	observer position
y_i	source position
y^+	normalized wall normal distance
α	observer angle
β	$\sqrt{1-M_0^2}$
δ	boundary layer thickness
δ_f	bandwidth
$\delta^\star$	boundary layer displacement thickness
$\delta_{x,y}$	interrogation window size
θ	enclosed trailing-edge angle
κ	von Karman constant
λ	wavelength of zig-zag tripping device
ν	viscosity
ρ	density
τ	relaxation time
Φ	power spectral density
ω	LBM weight function

scale of the individual turbulent eddies [3]. In the case of a developed turbulent boundary layer, the surface pressure is only affected within a confined area by various turbulent eddy sizes and, therefore, the overall aerodynamic force acting on the airfoil remains comparatively constant [3]. Due to the small length scale and high convective velocity of the eddies, this situation is typically encountered at high frequencies with respect to the human ear frequencies of interest. At such high frequency, where non-compactness arises due to the fact that the acoustic wavelengths are much smaller than the airfoil chord, the directivity pattern of the acoustic radiation shows a bias towards the leading edge (i.e. in upstream direction) [2,3]. For convecting turbulent boundary layers over sharp trailing edges, where the spanwise correlation associated with turbulent eddies is by far smaller than the airfoil span, an appropriate length scale is the local boundary layer displacement thickness $\delta^\star$ [4].

A slightly different situation is encountered for an asymmetrically beveled trailing edge, which is defined by the trailing-edge angle θ and the radius of curvature R, normalized by the maximum airfoil thickness h. For the special case of an obtuse corner, the radius of curvature is identically zero ($R=0$). This model was selected as the test case for the present study and Fig. 1 shows the truncated trailing-edge section. For asymmetrically beveled trailing edges with small radius of curvature, flow separation is observed over the beveled surface upstream of the trailing edge [3,5–7]. This flow separation can introduce a shedding component into the wake flow, which is associated with coherent vortex roll-up and velocity fluctuations at a shedding frequency f_s. The associated length scale is often characterized in terms of the wake thickness parameter or by the plate thickness h. If the bluntness $h/\delta^\star$ (>3.3) is large, the tonal noise component associated with such coherent vortex shedding becomes a dominating feature of the acoustic emission [3]. For the case of the obtuse corner, the separation point is fixed at the upstream corner point on the upper surface and its location is therefore independent of Reynolds number [7]. Beveled trailing-edge geometries have served for validation purposes in the past, for instance in the studies of Wang and Moin [8–10] and Shannon and Morris [5,6].

Several authors, for instance Amiet [11] and Howe [12], have discussed trailing-edge noise in the light of incident turbulent flow and diffraction theory, respectively. Within this framework, the relevant characteristics for noise radiation due to boundary layer interaction with the trailing edge are the auto-spectral density (ASD), the spanwise correlation length (l_z) of the unsteady surface pressure, and its convective velocity, which are all a function of frequency ω. Amiet [11] and Howe [12] assumed that the incident pressure gust on the surface of the airfoil convects past the trailing edge, which represents an impedance discontinuity and at which the fluctuations are scattered in the form of acoustic waves. This theory forms the start of multiple experimental and numerical studies, such as the Large Eddy Simulations (LES) of Christophe [13] and van der Velden et al. [14], the surface pressure measurements of Brooks and Hodgson [15], and the recent study of Pröbsting et al. [16,17], who proposed a methodology for trailing-edge noise diagnostics based on high-speed tomographic Particle Image Velocimetry (PIV). Numerical studies towards the prediction of beveled trailing-edge noise have been presented by Wang and Moin [8] and by van der Velden et al. [18,19]. However, simulations using conventional equations (as the Navier–