Technical University of Denmark

Study of airfoil trailing edge bluntness noise

Zhu, Wei Jun; Shen, Wen Zhong; Sørensen, Jens Nørkær

Published in:
The Scienceof Making Torque from Wind 2010

Publication date:
2010

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Zhu, W. J., Shen, W. Z., & Sørensen, J. N. (2010). Study of airfoil trailing edge bluntness noise. In The Scienceof Making Torque from Wind 2010: Torque 2010 (pp. 93-100)

Study of Airfoil Trailing Edge Bluntness Noise

Wei Jun Zhu
Technical University of Denmark, Fluid Mechanics
DK-2800 Lyngby, Denmark
wjz@mek.dtu.dk

Wen Zhong Shen
Technical University of Denmark, Fluid Mechanics
DK-2800 Lyngby, Denmark
shen@mek.dtu.dk

Jens Nørkær Sørensen
Technical University of Denmark, Fluid Mechanics
DK-2800 Lyngby, Denmark
jns@mek.dtu.dk

Abstract

This paper deals with airfoil trailing edge noise with special focus on airfoils with blunt trailing edges. Two methods are employed to calculate airfoil noise: The flow/acoustic splitting method and the semi-empirical method. The CAA based flow/acoustic splitting method is derived from compressible Navier-Stokes equations. It provides us possibilities to study details about noise generation mechanism. The formulation of the semi-empirical model is based on acoustic analogy and then curve-fitting with experimental data. Due to its high efficiency, such empirical relation is used for low noise airfoil design or optimization. Calculations from both methods are compared with existing experiments. The airfoil blunt noise is found as a function of trailing edge bluntness, Reynolds number, angle of attack, etc.

Keywords: Aeroacoustics, Airfoil trailing edge blunt noise

1 Introduction

Noise generation from wind turbines is known as an important issue. The new generation of wind turbines have larger rotor size that brings noise emission as a more crucial topic. Therefore design of an airfoil or blade must include aerodynamic noise generation as one of the parameter. High aerodynamic performance has been considered as the key in the designer's strategy. However, it is to a certain degree that too high aerodynamic noise emission limits the design of tip speed ratio or the rotor speed. It is clear that low noise airfoil with high aerodynamic performance is highly of our interest. Previous work by Bak et al.[1] has shown the strategy for such optimum design purpose. Different noise prediction models exist which are able to be coupled with aerodynamic design tools. A semi-empirical noise prediction model of Zhu et al. [2] was applied to optimize a 2 MW wind turbine [3]. The TNO [4,5] trailing edge model was applied in the airfoil design process by Bak et al. [1]. The work done by Shen et al. [6,7,8,9] was based on full numerical simulations where acoustic equations are derived directly from the original compressible Navier-Stokes equations. This method referred to the flow/acoustic splitting technique. The splitting technique was further developed by Zhu et al. [10,11] with the implementation of high-order schemes to acoustic equations. By using the current noise prediction tools [2, 6-11], airfoil blunt noise is investigated in the present paper.

The high frequency blunt trailing edge is generated due to the passage of trailing edge vortices from the unstable wake shear layer. The separated flow around the blunt trailing edge is quite unstable; it rolls up and down and later breakdowns into wake turbulence. This issue was studied experimentally by Brooks and Hodgson [12] using NACA 0012 airfoil. The experimental work of [12] provided reliable data for further parametric dependences study. Later on, Brooks et al. [13] proposed the semi-empirical models for individual airfoil self-noise mechanisms. The semi-empirical model was implemented into wind turbine noise generation model [2] and it fits well with some measured wind turbine noise data. However, we have also found that the model produces too high blunt noise level in several wind turbine noise prediction cases [3, 14]. Therefore a modified formulation to predict blunt trailing edge noise is also proposed in the present study.

The paper is organised as follows. At first, the CAA method is demonstrated to compute a blunt NACA 0012 airfoil and the solutions are compared to measurements. A NACA 63418 airfoil with two types of blunt trailing edge is then studied using CAA in order to capture the difference of their noise spectra. Secondly, the semi-empirical model is investigated and a modified blunt noise model is proposed. Conclusions are drawn in the final section.

2 CAA computations

The CAA method used here is based on decomposition of compressible Navier-Stokes equations into incompressible flow part and acoustic part [15]. The formulation of acoustic equations is remedied by Shen & Sørensen [16] by introducing a source term. By neglecting the viscous terms, the acoustic equations are written in a conservative form such as follows

$$\frac{\partial Q}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}+\frac{\partial G}{\partial z}=S \qquad (1)$$

where the vectors *Q*, *E*, *F*, *G*, *S* are given in equation (2). In the matrices the quantities with a superscript (') indicate acoustic variables and the capital letters U, V, W and P are flow variables. The sound speed in equation (2) is calculated at each time step using $c=\sqrt{\gamma(P+p')/\rho}$ where γ is the specific heat ratio. The acoustic computation can be started at any time after the flow computation is started. At each time level, the flow parameters form the input to the acoustic equations.

$$Q=\begin{pmatrix}\rho' \\ \rho u'+\rho' U \\ \rho v'+\rho' V \\ \rho w'+\rho' W \\ p'\end{pmatrix},$$
$$E=\begin{pmatrix}\rho u'+\rho' U \\ \rho(2Uu'+u'^2)+\rho' U^2+p' \\ \rho(Vu'+Uv'+u'v')+\rho' UV \\ \rho(Wu'+Uw'+u'w')+\rho' UW \\ c^2(\rho u'+\rho' U)\end{pmatrix},$$
$$F=\begin{pmatrix}\rho v'+\rho' V \\ \rho(Vu'+Uv'+u'v')+\rho' UV \\ \rho(2Vv'+v'^2)+\rho' V^2+p' \\ \rho(Vw'+Wv'+v'w')+\rho' VW \\ c^2(\rho v'+\rho' V)\end{pmatrix}, \qquad (2)$$
$$G=\begin{pmatrix}\rho w'+\rho' W \\ \rho(Wu'+Uw'+u'w')+\rho' UW \\ \rho(Wv'+Vw'+v'w')+\rho' VW \\ \rho(2Ww'+w'^2)+\rho' W^2+p' \\ c^2(\rho w'+\rho' W)\end{pmatrix},$$
$$S=\begin{pmatrix}0 \\ 0 \\ 0 \\ 0 \\ -\frac{\partial P}{\partial t}\end{pmatrix}.$$

In the following CAA calculations, the incompressible Navier-Stokes equations are solved by the second-order finite difference EllipSys code [17,18] and the acoustic equations are solved by 6^{th}-order optimized compact scheme [11]. In the first case, we calculate blunt trailing edge noise from a NACA 0012 airfoil with bluntness at about 0.35% of chord. The computational mesh is shown in Fig. 1. A two-dimensional structured body-fitted O-mesh is generated with about 150,000 cells. The computational grid in the radial direction is exponentially clustered on the airfoil surface. At the trailing edge, the upper and lower edges are rounded and a flat edge between the rounded edges (see Fig.1). Computations are carried out at two Reynolds numbers 1.6×10^6 and 2.8×10^6 with same angle of attack at 0^0. Small scale turbulence structures are modeled with a Sub-Grid Scale (SGS) model for Large-eddy Simulation (LES). In the current study, the two-dimensional version of the mixed model developed by Ta Phuoc [19] is used. The eddy viscosity is calculated using the mixed-scale turbulence model such that $\nu_t = C|\overline{\omega}|^{\alpha} k^{(1-\alpha)/2}\Delta^{(1+\alpha)}$ where ω is the vorticity, *k* is the turbulent kinetic energy, Δ is an average grid size and the constants are *C* = 0.02 and α = 0.5. For more details, the reader is referred to [19, 20]. The acoustic simulation is started after the flow is fully established. The acoustic pressure signal is stored in a data file at every time step in order to perform FFT later. The two acoustic pressure signals are selected at 0.05-chord above and behind the trailing edge. FFT is performed after a non-dimensional time of 20. The two selected acoustic pressure signals turn out to be quite similar. The resulted sound spectra are given in Fig. 2. The CAA calculations are seen to be able to capture the influence due to trailing edge bluntness. Fig.2 (a) and (b) display together the CAA results and the measurements. It is observed that the blunt trailing edge produces noise at high frequency range and shift towards higher frequency while Reynolds number increases.

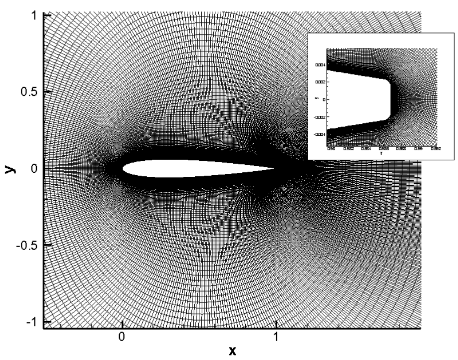
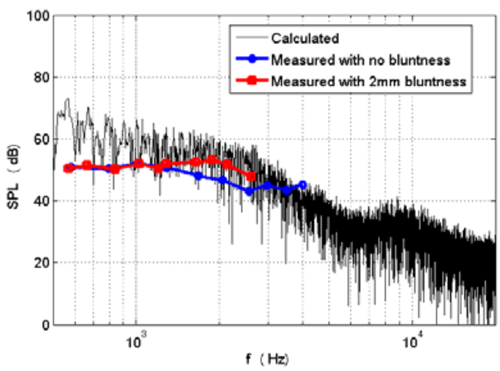
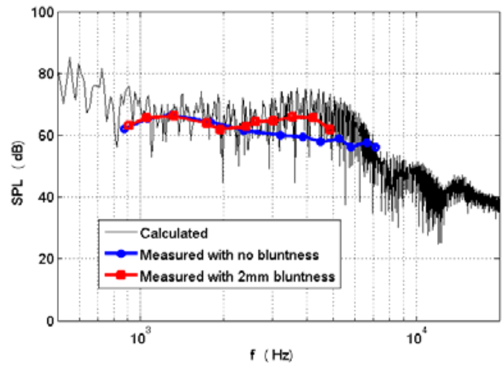


Figure 1: Computational mesh for a blunt NACA 0012 airfoil.



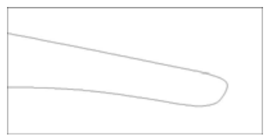
(a)



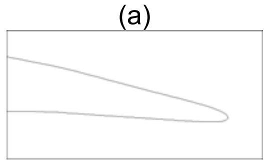
(b)

Figure: 2 Calculated noise spectrum compared with the experiments [12] at two wind speeds (a) U = 38.6 m/s and (b) U = 69.5 m/s.

In the next case, we consider a NACA 63418 airfoil with two trailing edge geometries as given in Fig. 3. Since NACA 63418 is the airfoil often used for wind turbine blade design, we carry out this computation to figure out the influence by changing trailing edge shape. Similar mesh configuration is used for the present study. Flow and acoustic simulations were carried out at zero angle of attack with a Reynolds number of $1.0{\times}10^6$. The two trailing edges differ from each other by means of the solid angle Ψ. The trailing edge of Fig. 3 (a) is much more 'flat' compare to Fig. 3 (b), therefore $\Psi \approx 0^0$ for case (a) and $\Psi \approx 20^0$ for case (b). The calculated sound spectra are shown in Fig. 4 where the effect of trailing edge bluntness is clearly seen. The 'flat' trailing edge (Fig. 3 (a)) produces distinguishable blunt noise as compared to the sharp one (Fig. 3 (b)). From CAA calculations we conclude that blunt noise exists for airfoils of nonzero bluntness. The sound level is proportional to the thickness and the solid angle Ψ. This solid angle Ψ is discussed in the next section which raises problem when using a semi-empirical model.



(a)



(b)

Figure 3: NACA 63418 with trailing edge shape of (a) and (b).

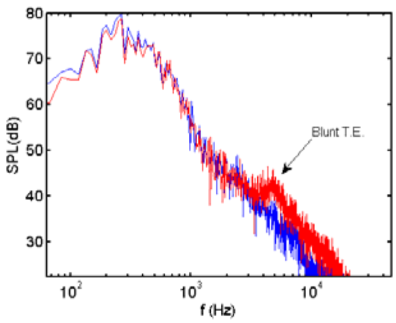


Figure 4: CAA calculation of sound spectra corresponds to geometry shown in Fig. 3.

3 Semi-empirical model

The semi-empirical noise prediction models are fast and robust and have been widely used for engineering purposes. The airfoil noise prediction model based on Brooks et al. [13] has been successfully applied to a wind turbine noise prediction model [2,3]. The model captures quite well the broadband noise of several wind turbines. However we have found that it produces too high level of blunt noise in several wind turbine noise prediction cases [3, 14]. Fig. 5 is an example of noise prediction of a 2 MW wind turbine. The prediction has good agreement with measurement except that the blunt noise is highly over predicted. The model input uses NACA 63418 profile as outer part of the blade which is responsible for the high level of blunt noise. In the previous section we have already calculated blunt noise from NACA 63418 using CAA, see Fig.4. It has not shown very high blunt noise level either with $\Psi \approx 0^0$ or with $\Psi \approx 20^0$. In real life, the blade profiles at trailing edge often have large similarity with the case shown in Fig. 3(a). Thus, a small trailing edge solid angle is used in the semi-empirical model, e.g. $\Psi \approx 0^0$. Fig. 6 shows the prediction of very high blunt noise with an input of $\Psi = 0^0$. When this airfoil is applied to a wind turbine blade at outer part, it yields the same kind of blunt noise prediction as seen in Fig. 5 where bluntness noise is predicted but is not seen from measurement.

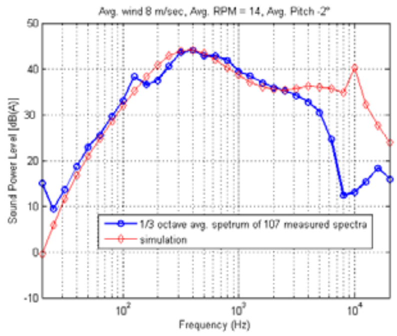


Figure 5: Sound power level of a wind turbine predicted with semi-empirical tool and compared with measurement at 100 m downwind.

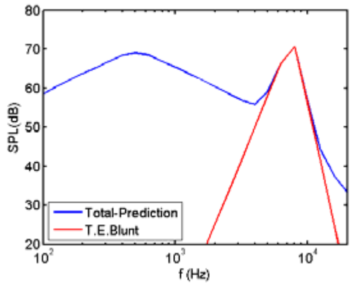
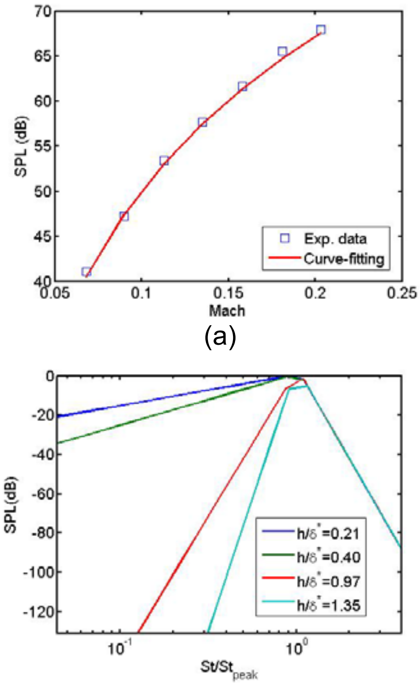


Figure 6: Semi-empirical prediction of blunt trailing edge noise of NACA 63418 airfoil with $\Psi \approx 0^0$. Predicted at 1 m above trailing edge.

The semi-empirical blunt noise model of Brooks et al. [13] was developed by scaling the experimental data. Any kind of trailing edge geometry was represented by an interpolation between a NACA 0012 airfoil and a flat plate extension. The NACA 0012 airfoil has a solid angle of $\Psi \approx 14^0$ and the flat plate has an angle of $\Psi \approx 0^0$. Therefore, experiments were carried out for both solid angles and interpolation is applied for other airfoils with trailing edge angles between 0^0 and 14^0. A flat plate is mounted at the trailing edge to obtain results for $\Psi \approx 0^0$. This appears to be a problem for blunt noise prediction in real life since wind turbine blades do not have a flat plate as trailing edge. Thus, using an interpolation between two angles to represent trailing edge geometry seems too rough. Also, it won't be convenient for the model users since the input solid angle has to be measured. And this solid angle is often varying as trailing edge curvature which makes it more difficult to choose a proper angle. Our intention of modifying the original model is to get the correct boundary layer parameter at trailing edge and use it as a key parameter. The change of Mach number, angle of attack, trailing edge geometry should be well-represented by boundary layer thickness. The calculation of the trailing edge thickness is performed through XFOIL [21] using prescribed trailing edge geometry. Using the existing experimental data from [13], we fit the sound pressure level and the spectra shape as function of Mach number, Strouhal number and boundary layer displacement thickness etc.



(a)

(b)

Figure 7: (a) Sound pressure level as function of Mach number; (b) Shape function at various blunt thicknesses.

The sound pressure level increases while Mach number increases. The data is plotted in Fig. 7(a) where the curve-fitting indicates that equation (3) best fits with experiment data.

$$SPL \propto 10\log_{10} M^{5.7} \qquad (3)$$

Figure 7(b) describes the spectrum shape function where

$$St = fh/U \qquad (4)$$

$$St_{peak} = \begin{cases} 0.149/(1+0.235(h/\tilde{\delta}^*)^{-1} - \ldots \\ 0.0132(h/\tilde{\delta}^*)^{-2})\{if\ 0.2 \le h/\tilde{\delta}^*\} \\ 0.1(h/\tilde{\delta}^*) + 0.06\{if\ 0.2 > h/\tilde{\delta}^*\} \end{cases} \qquad (5)$$

In equation (4) and (5), *f* is frequency, *h* is the bluntness (T.E. thickness) at trailing edge, U is free stream velocity, $\tilde{\delta}^*$ is the averaged trailing edge displacement thickness of pressure and suction side. The proportionality between sound pressure level and boundary layer thickness is found as shown in equation (6).

$$SPL \propto 10\log_{10}\left(h/\tilde{\delta}^*\right) \qquad (6)$$

Thus, a general modified equation is obtained as shown in equation (7).

$$SPL = 10\log_{10}\left(\frac{s\cdot 2\sin^2(\theta/2)\sin^2\phi\cdot M^{5.7}}{(1+M\cos\theta)(1+0.2M\cos\theta)^2\cdot r^2}\right) + 20(1+M^2)\log_{10}\left(h/\tilde{\delta}^*\right) + S\left(h/\tilde{\delta}^*, St/St_{peak}\right) \qquad (7)$$

The modified equation is independent of the solid angle and is only a function of the bluntness *h* and the boundary layer displacement $\tilde{\delta}^*$. In Fig. 8, the modified blunt noise model is compared with the previous CAA computation as shown in Fig. 4. The new blunt noise model predicts much less sound pressure level as compared to the original one, and it has much better agreement with the CAA result.

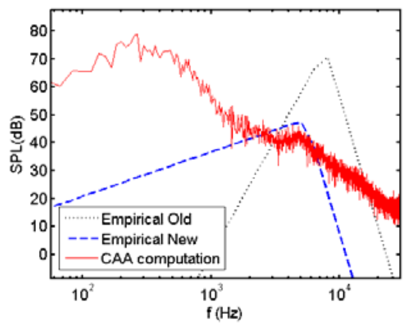
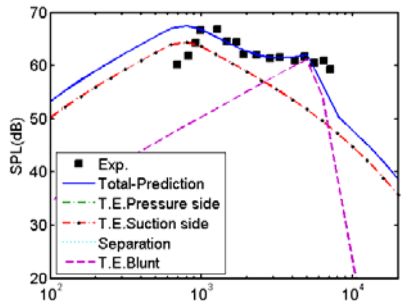
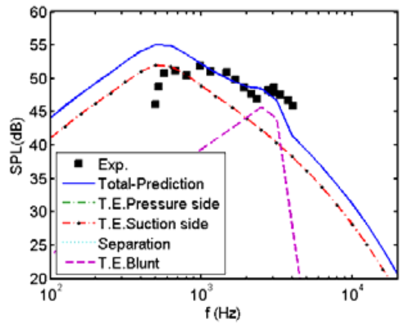


Figure 8: New blunt noise model compared with old model and the CAA computation.

To verify the equation, we compare the model with some experiments though Fig. 9 to Fig 11. In Fig. 9, the angle of attack is fixed at 0 degree and two inflow velocities are simulated. Due to the flow symmetry, the noise spectra of pressure side and suction side are superimposed and the separation noise does not appear. The overall noise level and the blunt noise level are more significant at U=70m/s. In Fig. 10, the flow velocity is fixed at U=70m/s and different angles of attack are considered. It is observed that airfoil blunt noise decreases when angle of attack increases. In Fig. 11 we apply the prediction model to a NACA 64418 airfoil. The blunt noise from NACA 64418 airfoil was observed in the experiments [22]. By assuming a similar bluntness as in Fig. 10, the model predicts quite well as compared with measured data.

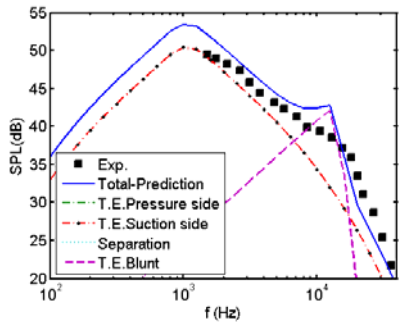


(a)

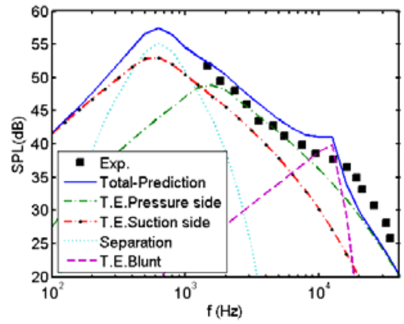


(b)

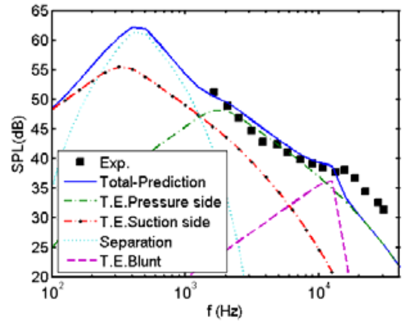
Figure 9: Comparison with ref.[13] pp. 82, Fig.98b and Fig. 99b. NACA 0012 airfoil, Chord=61cm, h=1.1mm, AoA = 0^0, U=70m/s (case (a)) and U=40m/s (case (b)).



(a)



(b)



(c)

Figure 10: Comparison with ref.[13] pp. 86, Fig. 103b, Fig. 104b and Fig105a. NACA 0012 airfoil, chord=40.6cm, h=0.38mm, U=70m/s, AoA = 0^0, 3.9^0, 6.1^0, for case (a), (b), (c) respectively.

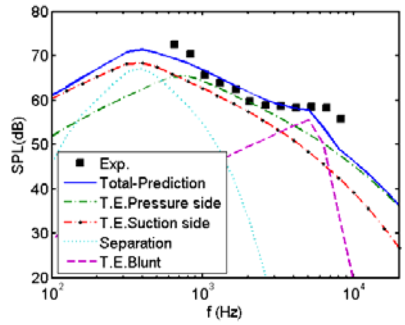


Figure 11: Comparison with ref.[22]. NACA 64418 airfoil, chord=80cm, AoA $=2.7^0$, U=60m/s, assumed TE bluntness of 0.1% chord, h=0.8 mm.

4 Conclusions

Airfoil trailing edge blunt noise is studied in the present paper. Both CAA and semi-empirical methods are able to predict noise from a blunt trailing edge due to the vortex shedding. CAA method provides more physical understanding of noise generation mechanisms which is also time consuming. The test cases shown in the paper indicate that the modified semi-empirical model is capable of predicting airfoil blunt noise. Such that it can be integrated into airfoil optimization code to design low noise airfoils. The general tendency of airfoil blunt noise is: (a) TE blunt noise level increases with Mach number; (b) TE blunt noise level increases with TE thickness; (c) The peak frequency decreases with TE thickness; (d) TE blunt noise level decreases with angle of attack.

5 References

[1] Bak, C., Bertagnolio, F. and Madsen H. Aa, "Design of Low Noise Airfoil with High Aerodynamic Performance'', Proceedings of Wind Turbine Noise Conference, Aalborg, June 2009.

[2] Zhu, W. J., Heilskov, N., Shen, W. Z. and Sørensen, J. N., "Modeling of aerodynamically generated noise from wind turbines", *J. Solar En. Engin ,2005,* 127, 517-528.

[3] Leloudas, G, Zhu, W. J., Shen, W. Z., Sørensen, J. N. and Hjort, S., "Prediction and Reduction of Noise from a 2.3 MW Wind Turbine", The Science of Making Torque from Wind. Journal of Physics: Conference Series 2007, 75, 012083

[4] Parchen, R., Progress report DRAW: A Prediction Scheme for Trailing-Edge Noise Based on Detailed Boundary-Layer Characteristics. 1998, TNO Rept. HAGRPT-980023 TNO Institute of Applied Physics, The Netherlands.

[5] Bertagnolio, F., Madsen, H. Aa and Bak, C., "Experimental Validation of TNO Trailing Edge Noise Model and Application to Airfoil Optimization", Proceedings of the European Wind Energy Conference and Exhibit, EWEC'09, Marseille.

[6] Shen, W. Z. and Sørensen, J. N., "Acoustic modeling of low-speed flows", *Theoretical and Computational Fluid Dynamics*. 1999, 13, 271-289.

[7] Shen, W. Z., Sørensen, J. N., "Aero-acoustic modelling of turbulent airfoil flows", *AIAA J.* 2001, 39, 1057-1064.

[8] Shen, W. Z. and Sørensen, J. N., "A collocated grid finite volume method for aeroacoustic computations of low-speed flow", *Journal of Computational Physics*, 2004, 196, 348-366.

[9] Shen, W. Z., Zhu, W. J. and Sørensen, J. N. "Aero-acoustic computations for turbulent airfoil flows", *AIAA. J*. 2009, 47, 1518-1527.

[10] Zhu, W. J., "Aero-Acoustic Computations of Wind Turbines", Technical Report, MEK-PHD 2007-09, Institute for Mechanics, Energy and Construction, Danish Technical University, Lyngby, 2008.

[11] Zhu, W. J., Shen, W. Z. and Sørensen, J. N., "High-order numerical simulations of flow induced noise", *Journal of numerical methods in fluids*, 2009, in print, 10.1002/fld.2241.

[12] Brooks, T. F., Hodgson, T. H., "Trailing edge noise prediction from measured surface pressures", *Journal of Sound and Vibration.*1981*,* 78, 69-117.

[13] Brooks, T. F., Pope, D. S., Marcolini MA, "Airfoil self-noise and prediction", 1989, NASA Reference Publication 1218.

[14] Leloudas, G., "Optimization of Wind Turbines with Respect to Noise", Technical Report, MEK-Msc 2006-11, Institute for Mechanics, Energy and Construction, Danish Technical University, Lyngby, 2006.

[15] Hardin, J. C. and Pope, D. S., "An acoustic/viscous splitting technique for computational aeroacoustics", *Theoretical and Computational Fluid Dynamics* 1994, 6, 323-340.

[16] Shen, W. Z., Sørensen, J. N., "Comment on the aeroacoustic formulation of Hardin and Pope", *AIAA J.* 1999, 1, 141-143.

[17] Michelsen, J. A., "Basis3D – A platform for development of multiblock PDE solvers", Technical Report AFM 92-05. Technical University of Denmark, 1992.

[18] Sørensen, N. N., "General purpose flow solver applied over hills", RISØ-R-827-(EN) Risø National Laboratory, Roskilde Denmark,1995.

[19] Ta Phuoc, L., "Modèles de sous maille appliqués aux ecoulements instationnaires décollés", Proceedings of the DRET Conference, Aérodynamique Instationnaire Turbulente-Aspects Numériques et Expérimentaux, Paris, France, 1994.

[20] Sagaut, P., "Large eddy simulation for incompressible flows", 3rd ed., Springer: New York, 2006.

[21] Drela, M., "XFOIL. An Analysis and Design System for Low Reynolds Number Airfoils", *Conference on Low Reynolds Number Aerodynamics*, University Notre Dame, 1989.

[22] Herrig, A., Würz, W. and Wagner, S., "Silent Rotors by Acoustical Optimization", University of Stuttgart, Laminar wind tunnel work package: No.5, 2003.