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S. Oerlemans, J.G. Schepers*, G. Guidati** and S. Wagner**

* Energy Research Centre of The Netherlands ECN, The Netherlands
** Institut für Aerodynamik und Gasdynamik (IAG) Universität Stuttgart, Germany

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Contents

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List of abbreviations

DATA	Design and Testing of Acoustically Optimized Airfoils for Wind Turbines
DLR	German Aerospace Laboratory
DNW-LLF	German-Dutch Wind Tunnel – Large Low-speed Facility
DU	airfoil profile code
ECN	Energy Research Centre of the Netherlands
FFA	airfoil profile code
IAG	Institute for Aerodynamics and Gasdynamics (Stuttgart University)
NACA	airfoil profile code
NLR	Dutch Aerospace Laboratory
PHATAS	aeroelastic wind turbine code
PVOPT	aerodynamic wind turbine design code
RE	reference airfoil
ROSI	ROtating Source Identifier
RPM	Revolutions Per Minute
TE	Trailing Edge
X1-X5	optimized airfoil shapes
XFOIL	airfoil design code

EXPERIMENTAL DEMONSTRATION OF WIND TURBINE NOISE REDUCTION THROUGH OPTIMIZED AIRFOIL SHAPE AND TRAILING-EDGE SERRATIONS

S. Oerlemans
National Aerospace Laboratory NLR
PO Box 153, 8300 AD, Emmeloord, The Netherlands

J. G. Schepers
Energy Research Centre of the Netherlands ECN
PO Box 1, 1755 ZG Petten, The Netherlands

G. Guidati, S. Wagner
Institut für Aerodynamik und Gasdynamik (IAG), Universität Stuttgart
Pfaffenwaldring 21, D-70550 Stuttgart, Germany

ABSTRACT: The objective of the European project DATA (Design and Testing of Acoustically Optimized Airfoils for Wind Turbines) is a reduction of trailing-edge (TE) noise by modifying the airfoil shape and/or the application of trailing-edge serrations. This paper describes validation measurements that were performed in the DNW-LLF wind tunnel, on a model scale wind turbine with a two-bladed 4.5 m diameter rotor which was designed in the project. Measurements were done for one reference- and two acoustically optimized rotors, for varying flow conditions. The aerodynamic performance of the rotors was measured using a torque meter in the hub, and further aerodynamic information was obtained from flow visualization on the blades. The acoustic measurements were done with a 136 microphone out-of-flow acoustic array. Besides the location of the noise sources in the (stationary) rotor plane, a new acoustic processing method enabled identification of dominant noise source regions on the rotating blades. The results show dominant noise sources at the trailing-edge of the blade, close to the tip. The optimized airfoil shapes result in a significant reduction of TE noise levels with respect to the reference rotor, without loss in power production. A further reduction can be achieved by the application of trailing-edge serrations. The aerodynamic measurements are generally in good agreement with the aerodynamic predictions made during the design of the model turbine.
Keywords: Noise, Aerodynamics, Test Methods.

1 INTRODUCTION

The most important noise source on a modern wind turbine is trailing-edge (TE) noise, which is caused by the interaction of the turbulent boundary layer with the trailing-edge of the blade. The objective of the European project DATA (Design and Testing of Acoustically Optimized Airfoils for Wind Turbines, [1]) is a reduction of TE noise by modifying the airfoil shape and/or the application of trailing-edge serrations. While the concept of TE noise reduction by serrations [2] has already been investigated in earlier projects [3,4], the concept of noise reduction by an optimized airfoil shape is relatively new.

The airfoil design procedure used in DATA was based on a TE noise prediction model described in [5]. Using this model a parametric study was performed of the relationship between integral boundary layer parameters (from the airfoil design code XFOIL) and TE noise. This study showed that the boundary layer at the trailing-edge should be thin and attached for low TE noise levels [6]. Applying this idea, two rounds of airfoil design were carried out within DATA. The goal was to design an airfoil which has the same aerodynamic characteristics as the reference airfoil (RE), but produces 3-6 dB less noise. As a reference the NACA-64418 airfoil was chosen since this is a common airfoil on modern wind turbines.

The first design round resulted in the airfoils X1 and X2, which were tested (2D) in NLR's Small Anechoic Wind Tunnel (Reynolds number $Re=10^6$, lift coefficient $c_l=0.7$). The test results showed a TE noise reduction (with respect to the reference airfoil RE) of about 2 dB for X1, which could be increased to about 4 dB by mounting TE serrations. Applying the same design principle as for X1, the second design round resulted in the airfoils X3 and X4, which were tested (2D) in wind tunnels at IAG and DLR ($Re=1.6\cdot10^6$, $c_l=1.0$). The test results showed noise reductions of 2-4 dB, which again could be increased by application of serrations.

It should be noted, however, that the reductions mentioned above were obtained for *untripped* conditions. Since the airfoil design was carried out for free transition, no TE noise reductions were measured for *tripped* conditions (except for serrations). Since for practical applications the tripped condition is more relevant, airfoil X5 was designed which should produce less noise in tripped conditions as well.

This paper describes the experiments that were performed in the DNW-LLF wind tunnel on a model scale wind turbine. The purpose of this test was to validate the noise reduction concepts developed in DATA and earlier projects in case of blade rotation and unsteady flow, since all earlier wind tunnel measurements were 2D. Acoustic and aerodynamic measurements were done for one reference rotor (RE) and two acoustically optimized rotors (X3 and X5), for a number of flow conditions and with and without leading-edge tripping. The optimized rotors were tested with and without TE serrations.

In Section 2 the test set-up will be described, including rotor design, experimental techniques, and an overview of the measurement program. The acoustic and aerodynamic results will be discussed in Section 3, followed by the conclusions in Section 4.

2 TEST SET-UP

2.1 Set-up in DNW-LLF wind tunnel

The experiments were done in the open jet test section of DNW-LLF with the 9.5x9.5 m^2 nozzle (see Figure 1). The test section was covered with foam wedges of more than 1 m. The distance between the nozzle and the rotor plane was 9 m.

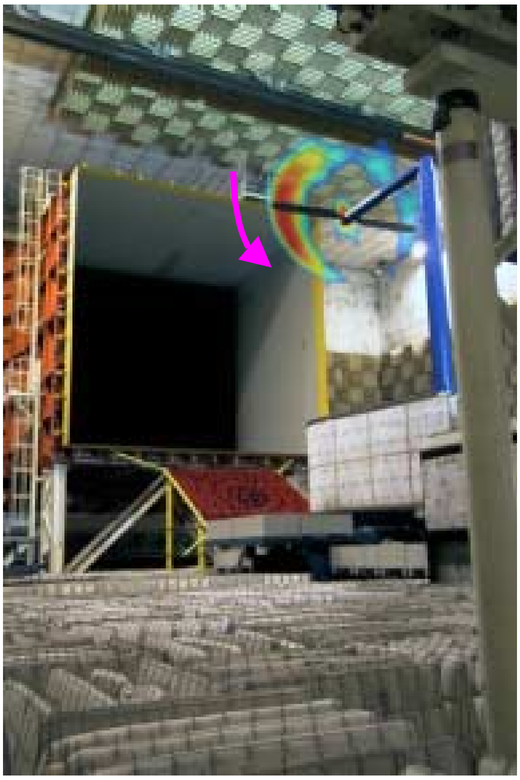

Figure 1: Test set-up with out-of-flow acoustic array and model scale wind turbine (looking upstream). The noise sources in the rotor plane (obtained from array data) are projected onto the picture.

2.2 Design of model scale wind turbine

In order to be representative for a full scale wind turbine, ideally the Reynolds number, solidity, and local tip speed ratio of the model rotor should be similar to the full scale situation. However, a number of restrictions had to be met with respect to rotor diameter (blockage effects), tip speed (compressibility effects), number of blades (test efficiency), and maximum tunnel speed. Hence, concessions had to be made to the representativeness of the model rotors.

The basic design aim for the model rotor was to maximise its annual energy production. This optimisation was performed with the program PVOPT [7]. The approach was to follow a procedure which is as much as possible comparable to the 'full scale' procedure, i.e. instead of scaling the optimized full scale design down, the optimization was performed directly for the wind tunnel situation (see [8]).

Taking the above considerations into account, the design parameters were defined as follows:

- Two bladed rotors with a diameter of 4.48 m
- Tip speed 100 m/s
- Tip chord 0.24 m
- Tunnel speeds between 11 and 16 m/s

These values lead to a tip Reynolds number of about 1.6 million, a solidity of 0.03, and a local tip speed ratio between 6 and 9. The distribution of airfoils along the blades was as follows:

- radius=0.0 to 0.5 m: no aerodynamic profile
- radius=0.5 to 0.9 m: DU91-W2-250
- radius=0.9 10 1.2 m: FFA-W3-211
- radius=1.2 to 2.24 m: NACA64418 (RE), X3, or X5

The rotor was driven by the tunnel flow, while the RPM was controlled with a hydraulic oil pump system. The nacelle diameter was 0.3 m, and the distance between tower and rotor plane was chosen to be 3 m to suppress aerodynamic interaction. A picture of the model rotor is given in Figure 2.

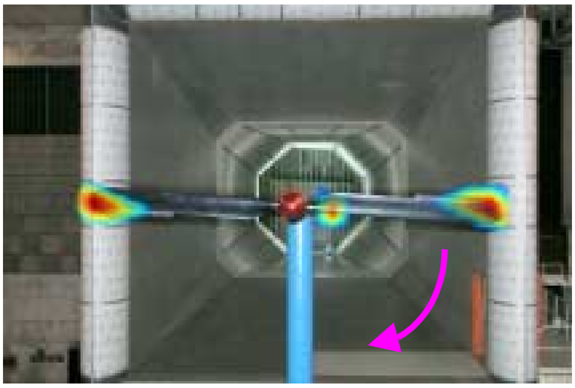

Figure 2: Model rotor with trailing-edge serrations, including projection of noise sources on rotating blades.

2.3 Experimental techniques and test program

Acoustic measurements were done using a 136 microphone 4x4 m^2 acoustic array, extended with four 1.5 m diagonal arms for extra resolution (see Figure 1). The microphone positions in the array were optimized for maximum side-lobe reduction [9]. Furthermore, the position and orientation of the out-of-flow acoustic array were optimized for maximum array resolution. The microphone signals were synchronously measured using the DNW/NLR data acquisition system [10], at a sample frequency of 48 kHz for 60 seconds per data point. The array data was processed in two different ways: the first method uses a conventional delay&sum algorithm to obtain the noise source distribution in the stationary rotor plane (see Figure 1). Secondly, a new method (ROSI-ROtating Source Identifier) was developed to identify (dedopplerized) noise sources on the rotating blades ([11], see Figure 2). The position of the blades was monitored using a pulse generator in the rotor hub.

The power produced by the rotor was measured with a torque meter in the hub, while a sublimation technique (using naphtalene) was applied to visualise the boundary layer transition region on the surface of the blades.

Measurements were done for the RE, X3, and X5 rotors, with and without leading-edge tripping (at 5% chord on both sides), for wind speeds between 11 and 16 m/s, RPM values of 424 and 540, yaw angles between -25 and +10 degrees, and blade pitch angles in a range of 3 degrees around the optimum angle. Furthermore, five different types of serrations were applied to the X3 and X5 rotors.

3 RESULTS AND DISCUSSION

In this section a limited number of representative experimental results will be presented and discussed. The results shown are for standard conditions, i.e. a wind speed of 14 m/s, an RPM value of approximately 424, a yaw angle of zero, and the optimum blade pitch angle. Section 3.1 deals with the acoustic results, in section 3.2 the aerodynamic results are discussed.

3.1 Acoustic results

A typical example of the noise source distribution in the stationary (RE) rotor plane is given in Figure 3. The grey circle indicates the position of the blade tips during rotation. Besides an extraneous mechanical noise source at the rotor hub for some frequencies, the plots clearly show a broadband aerodynamic source close to the tip. The array resolution can be seen to increase with frequency. Figure 3 also shows that for all frequencies most of the noise is radiated in the direction of the array when the blades move down, towards the array (see also Figure 1). This can be attributed to directivity and convective amplification.

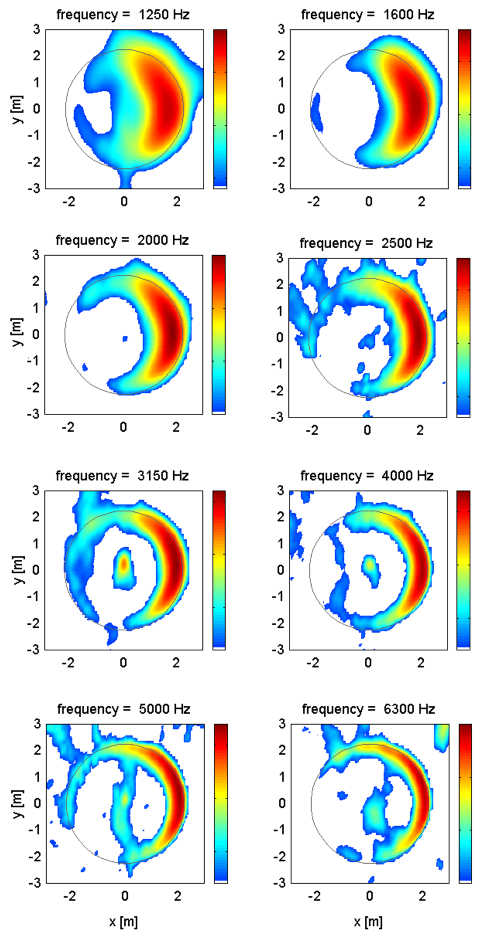

Figure 3: Noise source distribution in rotor plane for tripped RE rotor, standard conditions. The dynamic range is 15 dB.

Besides the standard array plots shown in Figure 3, the new processing method ROSI was applied to locate noise sources on the rotating blades. Typical examples of ROSI plots are shown in Figure 4, where the grey line indicates the contour of the rotor blade. The left column clearly shows that the broadband aerodynamic source already observed in Figure 3 is located at the trailing-edge of the blade. The resolution of the method is further illustrated in Figure 2, where an extraneous leading-edge source can be observed close to the root of one of the blades (probably due to the transition in airfoil at a radius of 0.5 m). The right column in Figure 4 shows the source distribution on the tripped X5 rotor blades (without serrations). Comparison with the left column shows an impressive broadband noise reduction with respect to the RE rotor, as a result of the optimized airfoil shape of X5. Repeat measurements showed that the levels in the ROSI plots for different blades and different conditions were reproducible within 1 dB.

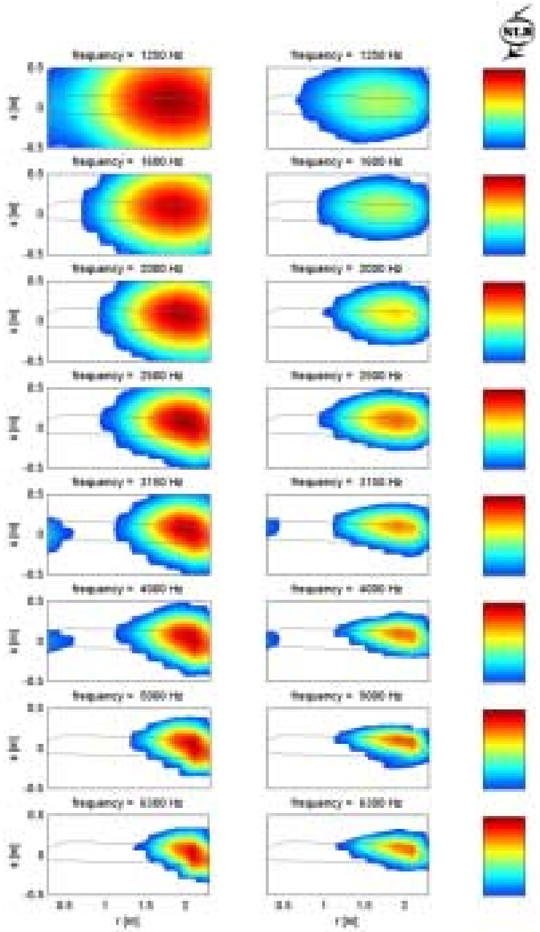

Figure 4: Noise source distribution on rotating blade (summed for both blades) for tripped RE rotor (left, compare with Figure 3) and tripped X5 rotor (right), standard conditions. The dynamic range is 15 dB.

Although the ROSI plots cannot be transferred to farfield levels straightforwardly (since the source area in the array plot may vary), comparison of the maximum levels in the ROSI plots gives an impression of the noise reductions obtained for the different rotors. This is shown in Figure 5, where the three rotors are compared for untripped and tripped conditions. As expected on the basis of the 2D wind tunnel experiments performed earlier in the DATA project (see section 1), for standard conditions the X3 rotor performs best (with regard to noise) in untripped conditions, while the X5 rotor performs best in tripped conditions. The noise reductions for other wind speeds, yaw angles, and pitch angles were similar or slightly less.

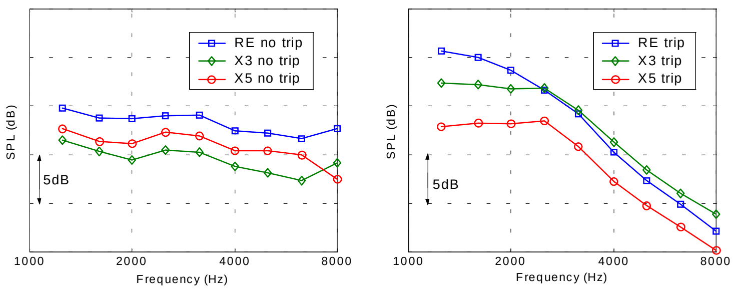

Figure 5: TE noise spectra (based on ROSI plots) for the three untripped (left) and tripped (right) rotors, standard conditions.

Finally, the effect of trailing-edge serrations is illustrated in Figure 6, which clearly shows the elimination of the TE noise source at the location of the serrations.

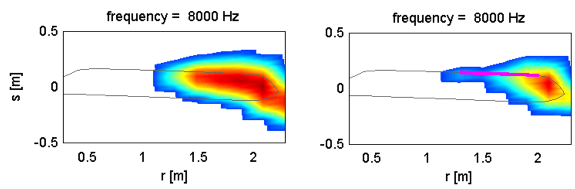

Figure 6: ROSI plot for untripped X5 rotor, standard conditions, without (left) and with (right) trailing-edge serrations. The pink line indicates the position of the serrations.

3.2 Aerodynamic results

Flow visualisation on the untripped rotors showed clear transition lines at roughly half-chord, extending over most of the blade up to the very tip. In case of tripping, flow visualisation confirmed boundary layer transition at the position of the trip (5% chord). Power measurements showed that the power produced by the X5 rotor was practically the same as RE for both tripped and untripped conditions, while the power of X3 was approximately 5% less. The measured power was generally in good agreement with the power predicted using the PHATAS program [12,13], as illustrated in Figure 7. For a more detailed discussion of the aerodynamic results and comparison with predictions one is referred to [8].

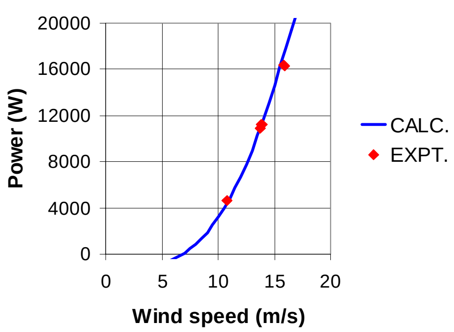

Figure 7: Comparison between measured and calculated power, untripped RE, standard conditions.

4 CONCLUSIONS

The conclusions can be summarised as follows:

- TE noise reduction by an optimized airfoil shape is possible: the average noise reduction achieved for varying conditions is about 4 dB
- optimized rotors show no significant loss in aerodynamic performance
- TE serrations give an extra reduction of 2-3 dB
- the new array processing method ROSI enables noise source location on individual rotating blades

5 ACKNOWLEDGMENT

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