Wind Tunnel Tests of Wind Turbine Airfoils at High Reynolds Numbers

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Abstract. Wind tunnel tests have been performed to measure the two-dimensional aerodynamic characteristics of two different airfoil families at high Reynolds numbers (from 3 to 12 millions) in the DNW High Pressure Wind Tunnel in Gottingen (HDG), Germany. Also, tests at a Reynolds number of 3 millions have been performed in the Low-Speed Low-Turbulence Wind Tunnel of Delft University, The Netherlands. The airfoils tested belong to two wind turbine dedicated families: the TU-Delft DU family and the ACCIONA Windpower AWA family that was designed in collaboration with CENER. Reynolds number effects on airfoil performance have been obtained in the range of 3 to 12 millions. The availability of data from two different wind tunnels has brought the opportunity to cross compare the results from the two facilities.

1. Introduction

2D wind tunnel tests of wind turbine dedicated airfoils have been performed in the scope of ACCIONA Windpower’s blade design activities. The tested airfoils correspond to two different airfoil families specifically designed for wind turbine blades. Three of them belong to the AWA family of ACCIONA Windpower which was designed in collaboration with CENER within the EOLIA project 2007-2010 (a Spanish Government funded project focused on the design of large offshore wind turbines for deep waters); these are the AWA18-1 (18% relative thickness), AWA21-1 (21% relative thickness) and AWA25-1 (25% relative thickness). The other two airfoils belong to the DU wind turbine dedicated airfoil family developed by Delft University of Technology [1] and are the DU 08-W-180 (18% relative thickness) and the DU 91-W2-250 (25% relative thickness).

ACCIONA Windpower, with the technical support of CENER, has performed the tests at two different facilities: the DNW-HDG High Pressure Wind Tunnel in Göttingen (HDG) and the Low-Speed Low-Turbulence Wind Tunnel (LST) at the Faculty of Aerospace Engineering of Delft University. Scientific insight from DNW-Göttingen and TU-Delft related to set-up, instrumentation, measurement techniques and data reduction process of the two wind tunnels has assured to get reliable results.
The aerodynamic coefficients have been calculated by integration of the static pressure distribution over the airfoil models, which were instrumented with pressure taps and by the integration of the momentum loss by means of a static and total pressure wake rake located downstream of the models.

Three airfoils, AWA18-1, DU 08-W-180 and DU 91-W2-250 have been tested at HDG at high Reynolds numbers, from 3 to 12 millions. Due to the increasing size of wind turbines rotors, especially in offshore applications, there is a need of getting knowledge of wind turbine airfoil behavior at high Reynolds numbers, as it can be stated from EU funded projects UPWIND, INNWIND or AVATAR. In addition to this, 2D airfoil wind tunnel test data at high Reynolds numbers (> 6 millions) and Mach regime (Mach ≤ 0.3) is mainly limited to tests performed on NACA airfoils in the nineteen thirties and forties in the NASA Langley Low Turbulence Pressure Tunnel (LTPT) [2].

The AWA airfoils plus the DU 08-W-180 have also been tested at Delft LST at a Reynolds number of 3 millions. This wind tunnel facility has been extensively used to perform 2D wind tunnel tests on wind turbine airfoils, which makes it possible to compare the AWA airfoils data with other wind turbine dedicated airfoils under the same conditions.

This paper starts making a description of the two wind tunnel facilities and the tests performed. Also, comparisons between data of airfoils tested at both wind tunnels at Reynolds numbers of 3 millions are shown. Finally, the impact of the high Reynolds numbers on the airfoils behavior is presented.

2. Tests Description
This section presents a description of the wind tunnel facilities, the tests performed and the corresponding models and instrumentation.

2.1. DNW-HDG

2.1.1. Wind Tunnel Description. The DNW-HDG High Pressure Wind Tunnel in Göttingen is a closed-circuit low-speed wind tunnel with a contraction ratio of 5.85. It can be pressurized up to 100 bars in order to achieve high Reynolds numbers. The speed range is 3.5 to 35 m/s and the maximum Mach number is 0.1. The turbulence level increases with speed (and therefore with Reynolds at constant chord) from 0.2% to 0.6%.

![Figure 1. DNW-HDG Wind Tunnel Layout](image)

The test section size is 0.6 x 0.6 m with 1 m length. It has two mechanically coupled turn tables flush with the side walls in order to horizontally mount the models with the centre of rotation in the
middle of the test section length. The centre of rotation for all the models has been set at c=0.035 m (35% of the chord). The reason to set this position instead of the typical 25% of the chord value was to have enough airfoil thickness for the mounting.

The free stream dynamic pressure is evaluated from the nozzle pressure drop, which is measured by hydraulically averaging 4 static pressure taps at the nozzle exist against the same number of pressure taps in the settling chamber, taking into account by calibration the boundary layer growth down to the centre of the test section.

The free stream total pressure is calculated using an absolute pressure reading in the settling chamber and the calculated free stream dynamic pressure.

Finally the free stream static pressure is calculated as the difference between the total pressure and the dynamic pressure.

2.1.2. Models and instrumentation. The instrumentation of the test models consists of 60 pressure taps distributed along the chord of the airfoils and a wake rake with 56 total and 6 static pressure probes installed downstream of the airfoil.

The Lift and Pitching Moment Coefficients are calculated by integration of the pressure distribution over the airfoil. For this purpose all the models were instrumented with 0.3 mm diameter pressure taps.

Drag is calculated from the flow loss of momentum by integrating the total and static pressures in the airfoil wake. They are measured by a wake rake located 3.5 chords (344 mm) downstream of the trailing edge of the model. It is positioned vertically and at 100 mm from the centre line of the test section, in order to avoid possible interference caused by the model pressure taps.

Additionally, measurements from 46 pressure taps, 23 on the top wall and 23 on the bottom wall and equally distributed over the length of the test section, are used to calculate wall interference properties. The method used is described in [3]. Measurements from the 3-component balance where taken to check the results of the pressure measurements for consistency.

**Figure 2.** One of the models tested in DNW-HDG

The HDG-airfoil models have a chord of 0.1 m and a span of 0.6 m (covering the entire test section width). All of them have been manufactured from steel. The models have cylindrical connections at both ends that are clamped to the turn table 3-component balance. Each model is equipped with a leveling block to set the zero angle of attack.

2.1.3. Testing procedure. Tests have been performed at Reynolds numbers of 3, 6, 9 and 12 millions. The data have been taken over the airfoil angle of attack range from -12° to 20°, with steps of 0.5° between 5° to 14° and 1° steps for the rest (except in the range from -6° to -12°, where steps of 2° have been used). Measurements were taken at static positions of each angle of attack, using an integration time of 30 s for each alpha point. Pressures were acquired using digital temperature compensated ESP.
scanners with ranges adapted to the maximum readings, being 5 psi for wake rake and wall, and 15 or 45 psi for the airfoil, depending on the dynamic pressure level. To gain necessary accuracy in the high pressured environment all pressures were measured against an in tunnel reference pressure, which reads a value of approximately the free stream static pressure. All pressure readings where acquired with the highest possible acquisition speed the INITIUM system allows for, which in the used configuration is 330 Hz and then averaged over the given integration time of 30 s. Only the averaged value is stored. The integration time was chosen after pre-tests in deep stall to give the most stable mean value.

Reynolds variation for 3 to 9 million was performed changing the speed at a constant tunnel pressure level of 46 bars. For the 12 million cases a higher tunnel pressure of 70 bars had to be chosen. Each polar started at 0º angle of attack to do the positive angles sweep up to 20º, then the 0º was repeated to start the negative angles sweep to -12º. After that, 0º, 2º and 4º angles of attack were repeated to check repeatability. Classical corrections following the formulas of Allen and Vincenty [4], as well as corrections calculated from wall pressure distribution [3] were calculated for each data point. Corrections were always below 1% of raw data values.

2.2. TU-Delft LST

2.2.1. Wind Tunnel Description. The TU-Delft Low-Speed Low-Turbulence Wind Tunnel is an atmospheric tunnel of the closed-throat single-return type, with a contraction ratio of 17.8. It has a 2.9 m diameter six-bladed fan driven by a 525 kW DC motor, giving a maximum test section velocity of about 120 m/s. The free-stream turbulence level in the test section varies from 0.02% at 25 m/s to 0.07% at 75 m/s. For these particular tests where 0.6 m chord models were used, these wind speeds corresponds respectively to Reynolds numbers of 1 million and 3 million.

The test section is 1.80 m wide, 1.25 m high and 2.60 m long. Electrically actuated turntables flush with the test-section top and bottom wall provide positioning and attachment for a two-dimensional model in the middle of the test section length. The centre of rotation for all the models is set at the half chord.

![TU-Delft Low-Speed Low-Turbulence Wind Tunnel Layout](image)

**Figure 3.** TU-Delft Low-Speed Low-Turbulence Wind Tunnel Layout

The free-stream dynamic pressure is evaluated through a calibration curve from the tunnel control pressure, which is measured as the difference between the settling chamber total pressure and the static
(wall) pressure at a station about halfway in the contraction. This static pressure at the contraction is evaluated as the average of 4 static pressure taps distributed at the circumference of the tunnel.

The free stream total pressure is calculated as an average of all the wake rake total pressures outside the wake.

Finally the free stream static pressure is calculated as the difference between the total pressure and the dynamic pressure.

2.2.2. Models and instrumentation. The measuring instrumentation of the tests consists of 90 pressure taps distributed along the chord of the airfoils and a wake rake with total and static pressure probes installed downstream of the airfoil. The models were positioned vertically in the test section, with the starboard side down.

The Lift and Pitching Moment Coefficients are calculated by integration of the pressure distribution over the airfoil. For this purpose all the models were instrumented with 0.3 mm diameter pressure taps distributed in two oblique sections on the port side of the model.

Drag is calculated from the flow loss of momentum by integrating the total and static pressure distribution in the airfoil wake. This was measured by a static and a total pressure wake rake, both 504 mm in width and located 0.82 chords (490 mm) downstream of the trailing edge of the model. The static wake rake consists of 16 static pressure probes. The total pressure wake rake had 67 pressure tubes with varying spacing ranging from 3 mm over 96 mm in the rake centre to 6, 12 and 24 mm towards both ends of the rake.

Both rakes are attached to a horizontal bar that crosses the entire test section. This bar can be electrically moved up and down in order to select the best span position for the measurement, and also it can be manually moved horizontally across the test section in order to center the wake rakes in the airfoil model wake.

The pressures were measured by a DTC INITIUM system containing ESP scanners. All pressures were read with a frequency of 330 Hz and averaged every 127 samples during a total averaging time of 10 s.

![Figure 4. One of the models tested in Delft LST](image)

The airfoil models have a chord of 0.6 m and a span of 1.25 m (spanning the entire test section height). The models have been made out of carbon fibre composites and covered with polyester gelcoat.

2.2.3. Testing procedure. The tests have been performed at a Reynolds number of 3 millions. Also tests at Reynolds numbers of 1 million have been performed for the AWA18-1 and the DU 08-W-180 airfoils.

The data has been taken over the airfoil angle of attack range from -15° to 20° (for 1 million Reynolds number polars, the range was increased to 30°). Angle of attack steps of 1° were taken, but in areas close to stall or drag-bucket corners, steps were smaller (0.5° or 0.25°).
Measurements were taken at static positions of each angle of attack, using an integration time of 10 s for each alpha point.

Each polar started at 0° angle of attack for a positive angles sweep up to 20°, then the 0° was repeated to start a negative angles sweep to -15°. Some angles of attack were repeated to check repeatability or additional points were taken to have enough density of measured points and increase curve smoothness. To the data the standard wind tunnel wall corrections for model and wake blockage and streamline curvature have been applied as given by Allen and Vincenti [4].

3. Wind tunnel comparisons

As some airfoils have been tested in both wind tunnels at the same Reynolds number (3 millions) a comparison of the characteristics is made to gain confidence in the results. Comparisons between different wind tunnel experiments have to be taken with care as not always the exact same conditions are achieved. Also, differences in the wind tunnel models, test set up, instrumentation or models aspect ratio and wall interference can lead to different results, especially in the non-linear region [5]. In this particular case, there are some key differences between the two tests that have to be outlined. Tests at HDG have been performed at very low Mach numbers (0.03 for Reynolds number of 3 millions) while at LST the Mach number was 0.23. The level of turbulence is lower at LST, being in the order of 0.07% while at HDG is in the order of 0.3% for the 3 millions Reynolds number condition. Model aspect ratio is 6 at HDG while at LST is 2.1. Another important issue to be considered, as it has a direct effect on the tunnel wall interference, is the model chord to test section height ratio (c/h) which in this case was lower at the HDG test (0.17 vs 0.36 at LST).

The following figures show the aerodynamic characteristic properties for the DU 08-W-180 at 3 million Reynolds number obtained from the two different wind tunnels, HDG and LST.

![Figure 5. DU 08-W-180 polar data at Re = 3\times10^6 for the two different wind tunnels.](image1)

![Figure 6. DU 08-W-180 lift coefficient at Re = 3\times10^6 for the two different wind tunnels.](image2)

The plots show good agreement between data from both experiments, especially when taking into account all the differences explained above. The lift curves show a slightly higher $C_l$ slope for the LST data. This is compatible with the different Mach number achieved in the wind tunnels.

There is also quite a similarity in the positive stall region. Deviations in the post-stall area could be explained by a 3D stall behaviour manifested as formation of stall-cells, whose number and size are
influenced by the aspect ratio of the model [8]. Also, the existence of stall cells can lead to different results depending on the span-wise positioning of the pressure taps.

Drag values show to be lower at LST. This is most probably an effect of the different turbulence levels attained in both facilities.

The next two figures show the results for DU 91-W2-250 airfoil tested at HDG and LST at 3 millions Reynolds number. In this case, the LST data don’t come from the ACCIONA Windpower tests, but from the DU-airfoils data base of TU-Delft.

Figure 7. DU 91-W2-250 polar data at \( \text{Re} = 3 \times 10^6 \) for the two different wind tunnels.

Figure 8. DU 91-W2-250 lift coefficient at \( \text{Re} = 3 \times 10^6 \) for the two different wind tunnels.

There is again a good agreement between data from both wind tunnels, and the comparisons follow the same trends as in the ones for DU 08-W-180 airfoil. This gives confidence in the results obtained in both experiments. It must be noted that the higher negative lift coefficient measured at the LST may be attributed to wind tunnel wall boundary layer interference effects. Measurements on a smaller model of the same airfoil in the LST measured at \( \text{Re}=1 \times 10^6 \) indicated that the negative maximum lift will be more in line with the HDG values.

Further work will be devoted to analyze in detail all the differences observed to try to derive more concrete conclusions about their origins.

4. The influence of high Reynolds numbers as measured in HDG experiment

The test performed at the HDG facility shows the influence of the Reynolds number in the aerodynamic coefficients for three different airfoils, the DU 91-W2-250, the DU 08-W-180 and the AWA18-1.

The tests have been performed at four different Reynolds numbers: \( \text{Re} = 3 \times 10^6, 6 \times 10^6, 9 \times 10^6 \) and \( 12 \times 10^6 \). The Mach number during these tests moved from 0.03 to 0.09.

From figure 9 to figure 14 the variation with Reynolds numbers of the lift and moment coefficient with respect to the quarter-chord point is presented for different angles of attack. Also the pressure distribution at 4º angle of attack for the three airfoils is shown. (4º angle of attacked is highlighted in the lift and moment coefficients curves)
Figure 9. DU 91-W2-250 lift coefficient and ten times moment coefficient for three Re numbers.

Figure 10. DU 91-W2-250 pressure coefficient for three Re numbers at 4° angle of attack.

Figure 11. DU 08-W-180 lift coefficient and ten times moment coefficient for three Re numbers.

Figure 12. DU 08-W-180 pressure coefficient for three Re numbers at 4° angle of attack.
The figures show that the maximum lift increases with Reynolds number, while the values of the moment coefficient have the same levels for each test. The lift-curve slope, in the angle of attack region between 0° and 5°, shows a slight increase with the Reynolds number. Similar trends can be observed in available experimental data at high Reynolds numbers [2], [6], [7].

An increase of the Reynolds number is expected to move the position of the laminar to turbulent transition forward to the leading edge of the airfoil. A detail of the pressure distribution of figure 15 is depicted in figure 16 to show the shift in transition location towards the leading edge as the Reynolds number is increased from 3 millions to 6 millions.

**Figure 13.** AWA18-1 lift coefficient and ten times moment coefficient for three Re numbers

**Figure 14.** AWA18-1 pressure coefficient for three Re numbers at 4° angle of attack.

**Figure 15.** DU 91-W2-250 pressure coefficient for two Re numbers.

**Figure 16.** DU 91-W2-250 pressure coefficient for two Re numbers; zoom showing suction side transition.
5. Conclusions

Wind tunnel tests of five airfoils from two different dedicated wind turbine airfoil families have been performed at high Reynolds numbers.

Comparison between measurements in two wind tunnel facilities, DNW-HDG and TU-Delft LST, at a Reynolds number of 3 millions show good agreement when taking into account the different test conditions, which gives confidence in the results obtained from the experiments.

The Reynolds effect in the range of 3 to 12 millions has been investigated showing an increase of the maximum lift coefficient for all airfoils under investigation, together with an increase of the angle of attack for maximum lift. For an angle of attack of 4° an upstream movement of the suction side transition position with increasing Reynolds number from 3 to 6 millions was shown.

References

[1] Timmer W A and Van Rooij R 2003 Summary of the Delft University wind turbine dedicated airfoils AIAA 2003-0352
[2] Abbott H I, et al 1944 Summary of Airfoil Data NACA report no.824
[3] Amecke J 1986 Direct calculation of wall interferences and wall adaptation for two-dimensional flow in wind tunnels with closed walls. NASA TM-88523
[4] Allen H J and Vincenti WG 1947 Wall interference in a two-dimensional wind tunnel, with consideration of the effect of compressibility NASA Report no. 782
[5] Timmer W A 2009 An overview of NACA 6-digit airfoil series characteristics with reference to airfoils for large wind turbine blades AIAA 2009-268
[6] Loftin K L Jr, Bursnall W J 1948 Effects of Variations in Reynolds Number Between $3.0 \times 10^6$ and $25 \times 10^6$ upon the Aerodynamic Characteristics of a number of NACA 6-Series Airfoil Sections NACA-TN-1773
[7] Sommers D M and Tangler J L 2000 Wind-Tunnel Tests of Two Airfoils for Wind Turbines Operating at High Reynolds Numbers NREL CP-500-27891
[8] Schewe G 2001 Reynolds-number effects in flow around more-or-less bluff bodies J. Wind Eng. & Ind. Aerodyn. 89 1267-1289