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SUMMARY OF THE DELFT UNIVERSITY WIND TURBINE DEDICATED AIRFOILS

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ABSTRACT

This paper gives an overview of the design and wind tunnel test results of the wind turbine dedicated airfoils developed by Delft University of Technology (DUT). The DU-airfoils range in maximum relative thickness from 15% to 40% chord. The first designs were made with XFOIL. Since 1995 RFOIL was used, a modified version of XFOIL, featuring an improved prediction around the maximum lift coefficient and capabilities of predicting the effect of rotation on airfoil characteristics. The measured effect of Gurney flaps, trailing edge wedges, vortex generators and trip wires on the airfoil characteristics of various DU-airfoils is presented. Furthermore, a relation between the thickness of the airfoil leading edge and the angle-of-attack for leading edge separation is given.

INTRODUCTION

During the last decade some fifteen wind turbine airfoils have been designed at DUT, of which 5 have been extensively tested in the Delft University wind tunnel (LST) and 4 in the low-speed wind tunnel of IAG Stuttgart. Two designs were tested in both wind tunnels to verify specific design features.
The goal of the LST-tests was twofold. First, they served as a validation of the design code and a verification of the capabilities of the code to predict specific airfoil features. Furthermore the effect on performance of aerodynamic devices such as Gurney flaps and vortex generators could be studied experimentally. As a result the airfoil designs are well documented and constitute a series of base airfoils from which other designs may be derived with confidence.

The airfoils, ranging from 15% to 40% relative thickness, have been developed in a number of projects, funded by the European Union in the framework of the JOULE program, the Netherlands Agency for Energy and the Environment (NOVEM) and by various European blade manufacturers. At present DU airfoils are being used by various wind turbine manufacturers world wide in over 10 different rotor blades for turbines with rotor diameters ranging from 29 m. to over 100 m.,

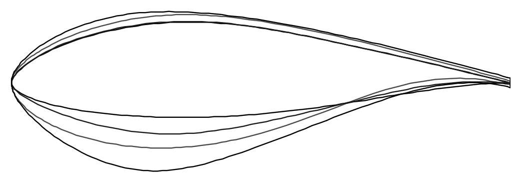

Figure 1: A series of DU airfoils for a pitch regulated 55 m diameter rotor.

corresponding to machines with maximum power ranging from 350 kW to 3.5 MW.

In the eighties and early nineties of the last century it was common practice to use existing airfoil families like the 4 digit NACA 44 and the 6 digit NACA 63 series for the design of wind turbine blades. The required thickness in the root was achieved by linearly scaling the coordinates from airfoils with smaller thickness. From calculations and wind tunnel tests it appeared, however, that the thick members of the NACA airfoil family suffer from a severe degradation of the performance due to premature transition. In his period research projects were conducted in various institutes in the US and Europe (e.g. [1] ,[2]) to produce alternatives for the widely used NACA airfoils, especially those with a maximum relative thickness of 21% or more. Three DU-airfoils result from this period, designated DU 91-W1-251, DU 91-W2-250 and DU 93-W-210.

In practice most wind turbine manufacturers tune the blades of stall-regulated machines with vortex generators and stall strips. Furthermore the application of Gurney flaps has been considered. In the Delft wind tunnel, tests were performed mostly on airfoil DU 93-W-210 to answer the resulting quest for data concerning the effect on airfoil performance and to give guidelines for locations and sizes of the various tuning devices.

With the growing knowledge of the mechanism behind wind turbine blade noise and the effect of rotation, although not yet fully understood, during the second halve of the nineties a number of airfoils was designed using an 18% thick tip airfoil with low maximum lift (DU 95-W-180) and a 30% thick inboard airfoil (DU 97-W-300) as base lines.

The general designation of the DU airfoils is DU yy-W-xxx, in which DU stands for Delft University, followed by the last two digits of the year in which the airfoil was designed, a W denoting the wind energy application, to distinguish the airfoil from the ones designed for sailplanes and general aviation and 3 digits giving 10 times the airfoil maximum thickness in percent of the chord. In the case of DU 91 there is an additional number following the W to denote that there has been more than one design with a thickness of about 25% that year.

The work on wind turbine airfoils at Delft University has been the subject of a number of contributions to consecutive European wind energy conferences, e.g. [3] to [6], where some of the subjects discussed in this paper can be found in more detail. In the following the design philosophy and experimental results for the DU airfoils will be presented.

EXPERIMENTAL SETUP AND PROCEDURE

Wind tunnel

The tests reported here were performed in the Low-speed Low-turbulence wind tunnel of the Faculty of Aerospace Engineering of Delft University, figure 2. The wind tunnel is of the closed single-return type with a total circuit length of 72.7 meters. The circuit has a contraction ratio of 17.8 to 1. The free-stream turbulence level in the 2.6 m. long, 1.25 m high and 1.80 m wide octagonal test section ranges from .02 % at a wind speed of 25 m/s to 0.07% at 75 m/s, equivalent with Reynolds numbers in the range from $1x10^6$ to $3x10^6$, using 0.6 m chord models.

A 580 kW DC motor, giving a maximum test section velocity of about 120 m/s, drives a 2.9 m diameter six-bladed fan. Electrically actuated turntables flush with the test-section top and bottom wall provide positioning and attachment for a two-dimensional model.

Models

The composite models had a chord of 0.6 m and completely spanned the height of the test section. Around 90 to 100 pressure orifices with a diameter of 0.4 mm. were installed in staggered formation. The polyester gelcoat surface of the models was sanded and polished. The contour of these particular models was not measured, however the deviation from the prescribed shape of similar models from the same manufacturer has always been well below 0.1mm.

Figure 2: The model of airfoil DU 97-W-300 in the LST test section seen from inside the contraction. The wake rake is in the back.

Instrumentation

The model static pressures and the wake rake static and total pressures were fed either to an electronically read 200 tubes liquid multi-manometer with fiber optic cells or an electronic pressure scanner system. Data were recorded using an electronic data acquisition system and were on line processed using the laboratory computer.
During the years a variety of wake rakes has been used ranging from a device with 50 total tubes and 12 static tubes with a width of 219 mm. to the present one having 67 total pressure tubes and 16 static pressure tubes over a length of 504 mm.

Force coefficients

The testing of each new model configuration started with a number of wake rake traverse measurements in span wise direction at various angles-of-attack and Reynolds numbers to confirm the two-dimensionality and to establish the wake rake position giving an average drag value representative for the model. The model pressure distributions were integrated to obtain normal force and tangential force coefficients C_n and C_t and moment coefficients C_m. Lift coefficients were computed using C_n and the wake rake drag according to equation 1. In the post stall region the pressure drag was used, computed from the pressure distributions.

$$C_l = C_n / \cos \alpha - C_d * \tan \alpha \qquad (1)$$

Wind tunnel wall corrections

To the measured data the standard wind tunnel wall corrections for lift-interference and model solid and wake blockage as given by Allen & Vincenti [7] were applied. Corrections have also been made for the effect of solid blockage of the wake rake on the test section velocity and the effect of the wake rake self-blockage on the values of the static pressures (and consequently the dynamic pressure) measured by the wake rake.
The standard position of the wake rake was about 60% chord length downstream from the model trailing edge.

Effects of roughness

As a standard way to check the sensitivity of the designs to contamination of the leading edge, 0.35mm thick zigzag tape was used. The tape leading edge was located at the model upper surface 5% chord station.
On average for the airfoils tested, at angles around the maximum lift-to-drag ratio, the critical height of distributed roughness as calculated by the method of Braslow [8] on the 5% chord location is in the order of 0.15 mm. For zigzag tape, having a critical Reynolds number based on roughness height of about 200 instead of 600 for grit roughness, the critical height would be about 0.10 mm. Although not being a roughness simulation of the worst kind, the zigzag tape of 0.35 mm thickness can therefore be considered as a rather severe means of tripping.

PREDICTION OF THE TWO-DIMENSIONAL AIRFOIL CHARACTERISTICS

For the design of the Delft airfoils the XFOIL code was used. First in the basic version 5.4, after 1996 in a modified version called RFOIL. The RFOIL code resulted from a NOVEM funded project called TIDIS (Three Dimensional effects in Stall), carried out by the Netherlands Energy Research Foundation ECN, the National Aerospace Laboratory NLR and Delft University. The aim of the project was to develop a method on basis of the existing XFOIL code to calculate the effect of rotation on airfoil performance. To this end, first the code's prediction of the airfoil performance around the two-dimensional maximum lift was enhanced. Improvement of the numerical stability was effectuated by using the Schlichting velocity profiles for the turbulent boundary layer instead of Swafford's. Furthermore, the shear lag coefficient in Green's lag entrainment equation of the turbulent boundary layer model was adjusted and deviation from the equilibrium flow has been coupled to the shape factor of the boundary layer [9].

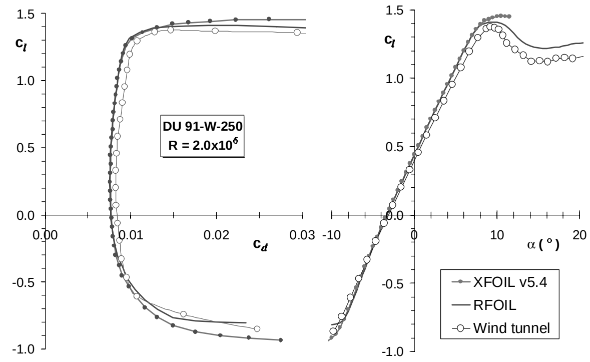

Figure 3: The prediction of DU 91-W2-250 characteristics with XFOIL and RFOIL

In figure 3 a comparison is made between the "old" XFOIL version 5.4 and the RFOIL code. The RFOIL result still not matches the measurements perfectly, but the trend in post stall (time-averaged) lift is fairly well predicted.

GENERAL DESIGN CONSIDERATIONS

Although eventually the characteristics of a wind turbine airfoil are a trade-off between several conflicting requirements, some properties can be identified as being generally desirable. The wish to keep the sensitivity of the airfoil to contamination and contour imperfections of the nose as low as possible has been the primary design driver for the Delft airfoils. In this light the maximum lift capacity of the designs has been held at a moderate level, to keep the loss in lift due to surface contamination as small as possible. Although the design Reynolds number is in the range of $2x10^6$ to $4x10^6$, this opens the possibility to use the airfoils in larger blades and consequently at higher Reynolds numbers as well. There is another reason to pursue moderate lift coefficients. Blades will seldom be clean and it may be questioned if the high-lift potential of blade airfoils will be addressed frequently.

DU 91-W2-250

The design of airfoil DU 91-W2-250 followed wind tunnel tests on a 25% thick NACA airfoil from the 63-4xx series, linearly scaled from 21% [10]. These tests showed a reduction in the maximum lift coefficient of 35% due to a tripped boundary layer on the 5% upper surface chord station. The poor performance of thick

NACA-airfoils with leading edge contamination can be traced to the high upper surface velocities and resulting high adverse pressure gradients due to the larger upper surface thickness, giving premature transition and early separation. The thick airfoils currently in use by most blade manufacturers all have a restraint upper surface thickness to avoid this premature turbulent separation. To compensate for the resulting loss in lift of the upper surface, a certain amount of lower surface aft loading is incorporated, giving the typical S-shape of the pressure side. It was the intention to use the new 25% thick DU-airfoil in stall as well as pitch blades for 500 kW machines with rotors of about 40 m diameter, which was still fairly large in the early nineties. This was translated into the following design goals:

- a $C_{l,max}$ of about 1.4 to 1.5 with a gradual stall,
- NACA airfoil (maximum C_l/C_d > 119)
- a low sensitivity to leading edge contamination by ensuring that the transition location is near the leading edge when approaching stall at a Reynolds number of $3x10^6$
- trailing edge thickness between 0.5% and 1%c
- location of maximum thickness around 30%c

There was no restriction on the moment about the quarter-chord point. The airfoil was designed with the

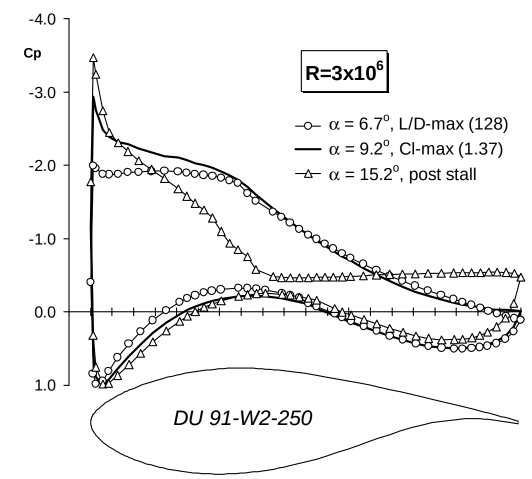

Figure 4: Measured pressure distributions for DU 91-W2-25 at R=$3x10^6$

earlier XFOIL version 5.4. Measured pressure distributions are given in figure 4 and the measured performance at R=$3x10^6$ is shown in figure 5. It appeared that the $C_{l,max}$ was just off the target of 1.4, although the calculations predicted a value of 1.53.

The sensitivity of the airfoil to distortion of the boundary layer at the nose was investigated by applying zigzag tape of 0.35 mm thickness at the 5% chord

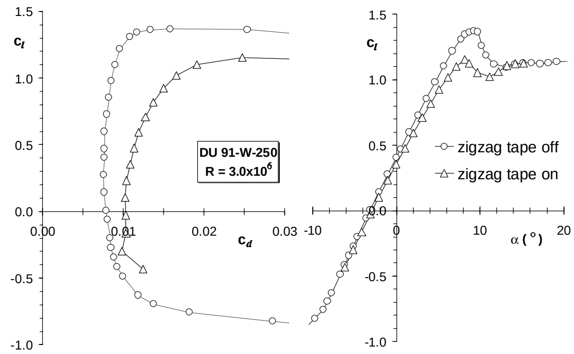

Figure 5: Measured airfoil performance of DU 91-W2-250 at R=$3x10^6$.

station. Due to the trip the maximum lift coefficient dropped from 1.37 to 1.16.

DU 93-W-210

To serve as an intermediate airfoil between DU 91-W2-250 and outboard airfoils with rather high camber such

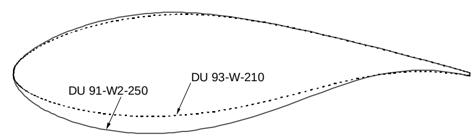

Figure 6: The airfoil shapes of DU 91-W2-250 and DU 93-W-210

as NACA 63_3-618, the 21% thick DU 93-W-210 was designed. The airfoil exhibits a maximum lift-to-drag ratio of 143 at R=$3x10^6$ and a maximum lift coefficient of 1.35. The airfoil model was extensively used to experimentally verify the effect of vortex generators, Gurney flaps and trip wires. Further on in this paper the results of this investigation will be highlighted. Figure 6

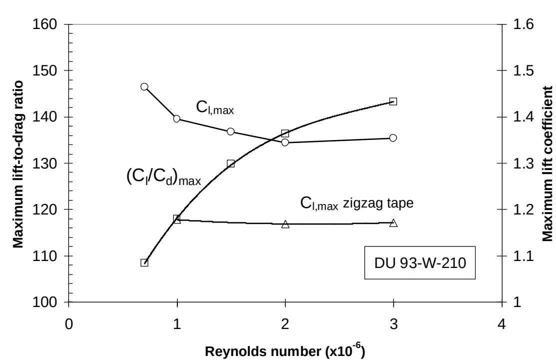

Figure 7: The effect of Reynolds number on the maximum lift-drag ratio and maximum lift coefficient of airfoil DU 93-W-210

depicts the difference between the contours of DU 91 and DU 93. The upper surface thickness of the DU 91 airfoil was generally maintained and the airfoil was made more laminar by shifting the location of maximum thickness a few percent backwards in favor of a high lift-to-drag ratio.
In figure 7 the maximum l/d and the maximum lift coefficient of DU 93 are depicted. Although the value of $C_{l,max}$ at a Reynolds number of $3x10^6$ was a little disappointing (1.35 instead of the predicted 1.45) the overall performance of the airfoil, however, certainly in terms of lift-to-drag ratio, was satisfying.

DU 95-W-180

Design considerations

For a pitch controlled wind turbine a high lift-drag ratio of the outboard airfoils is required. From the performance perspective the height of the C_l for maximum lift-drag ratio (the design-C_l) is relatively unimportant. The difference in terms of units C_l between the design-C_l and the $C_{l,max}$ must not be too much to prevent excessive loads in case of gusts and not too little to prevent the rotor from stalling when the pitch system is not fast enough. A difference between the two C_l's of about 0.2 is expected to be sufficient.

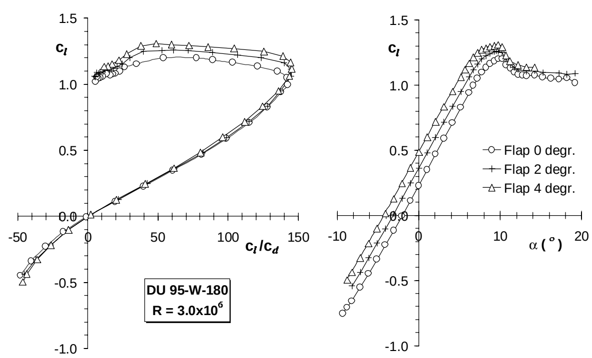

Figure 8: The effect of a flap deflection on the performance of DU 95-W-180 at R=$3x10^6$.

From the loads viewpoint a high design-C_l should be aimed at because this leads to smaller chords and consequently to lower storm loads. This, however, is contradictory to the wish to keep the airfoil's sensitivity to leading edge contamination low. In general outboard airfoils will not have maximum lift coefficients higher than 1.4 to 1.5. To have the possibility to use the airfoil in stall regulated rotors as well the $C_{l,max}$ was chosen to be 1.25. The required maximum lift to drag ratio was set at 140 at $3x10^6$ to compete with existing NACA-airfoils. To prevent excessive boundary layer noise the airfoil has a sharp trailing edge.

Wind tunnel results

Based on the fact that in earlier designs the $C_{l,max}$ was over predicted, the wind tunnel model was equipped with a 20% chord trailing edge flap to tune the lift performance.
The measured lift coefficients and accompanying lift-drag ratio's of the model with flap deflections of 0^o, 2^o and 4^o for a Reynolds number of $3x10^6$ are shown in figure 8. The base airfoil (zero flap deflection) appeared to have a maximum lift coefficient of 1.20, instead of the predicted value of 1.25, which however could be reached with a 2^o flap deflection. The latter configuration was later designated DU 96-W-180 and also tested at large angles-of-attack in a different test set-up [6] and in the low-speed wind tunnel of the Institut für Aero- und Gasdynamik of Stuttgart University, Germany. In figure 9 measured pressure distribution of DU 96-W-180 from the present test are given at angles specific to the airfoil performance. For

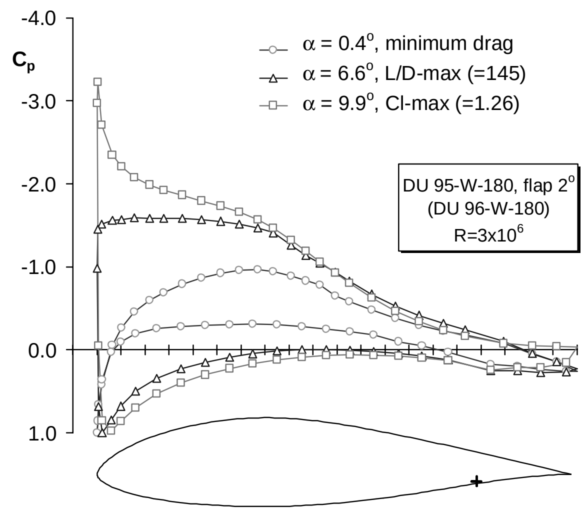

Figure 9: Measured pressure distributions of airfoil DU 96-W-180 at R=$3x10^6$.

clarity of the graph half of the pressure information has been omitted. The airfoil exhibits a high lift-to-drag ratio of 145 at R=$3x10^6$. Measurements in the Stuttgart low-speed wind tunnel at R=$4x10^6$ gave a $(C_l/C_d)_{max}$ of 149 and a $C_{l,max}$ of 1.32. The sensitivity of the airfoil to leading edge roughness is low, as can be deduced from figure 10 in which the effect of zigzag tape is shown. The loss in $C_{l,max}$ due to the increased momentum loss thickness is .09.

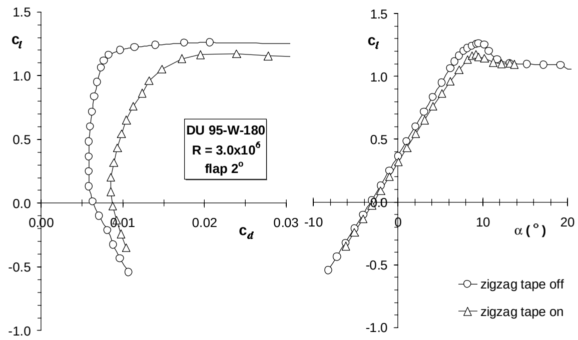

Figure 10: The effect of zigzag tape at x/c=0.05 on the performance of DU 96-W-180.

THICK AIRFOILS

For structural reasons significant section thickness is required in the root of the blade. Small root chords and restricted blade weight help to overcome problems of transportation of large blades and keep down structural loads on the shaft and bearings. This calls for airfoils with a high relative thickness, typically 30% to 40% chord. The inboard segment of the blade requires a high maximum lift coefficient to deliver sufficient torque at the lower wind speeds. To achieve high lift, the inner 50% span of the blades of stall controlled wind turbines is generally fitted with vortex generators (vg's) and numerous wind tunnel tests have revealed that vg's can easily boost the maximum lift coefficient to about 1.9. With the increasing tower height for the large machines the degree of contamination of the inner part of the blade by dirt or insects may be less serious.

Rotational effects

Thick airfoils are in that part of the blade subjected to rotational effects. It is virtually impossible, or at the least very difficult, to design thick airfoils and define their sensitivity to leading edge contamination if the effects of rotation cannot be quantified in some way.

RFOIL

As already mentioned the goal of the 1996 Dutch project TIDIS was to generate a code to calculate the effect of rotation using the strong viscous/inviscid interaction scheme of XFOIL. The integral boundary layer equations in XFOIL have been extended for radial flow based on the Snel-Houwink model for blade rotation. [11]. A Johnston cross flow velocity profile and additional closure relations were added. Convergence of the calculation restricted the adjustments to first and second order terms. The cross terms in the 3D boundary layer equations are driven by the local solidity c/r, which is used as input parameter.

The predictive value of RFOIL calculations has among others been verified against measurements performed by FFA on a 5.35 m diameter model rotor in the 12x16m. low-speed wind tunnel of the Chinese Aerodynamics Research and Development Center, CARDC. For the rotor blades the NACA 44 series of airfoils was used. Pressure distributions at various span locations were measured and integrated to normal force and tangential force coefficients C_n and C_t.

Because the angle-of-attack during the experiments was not known a match has been made between the measured C_n-C_t curves and those calculated by RFOIL. It was established that RFOIL tends to overestimate the rotational effect for a specific c/r value. Nevertheless, if 2/3 of the geometrical c/r value was used, it appeared that RFOIL was capable of predicting the pressure distribution on the rotating blade quite well. In figure 11 an example is given of the measured and calculated pressure distributions for a matched point in the C_n-C_t curve of the 30% span section at a Reynolds number of 420,000. The C_n and C_t values originate from a calculation of airfoil NACA 4424 at an angle-of-attack of 18°. The same trend emerged from comparisons with

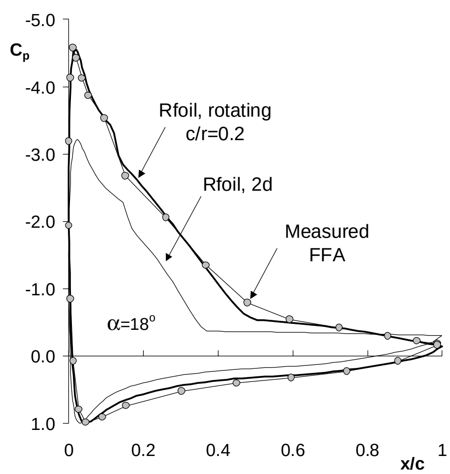

Figure 11: The predicted and measured effect of rotation on the pressure distribution of the 30% span section of a rotating blade

pressure distributions measured on the blades of the 10m. diameter two-bladed rotor of the Delft University field test installation. The blades incorporate the NLF(1)-0416 airfoil. It was felt that RFOIL could be used to generate airfoils for the inner 40% of the blade span and predict trends in roughness sensitivity and height of $C_{l,max}$ with airfoil thickness to a reasonable degree.

DU 97-W-300

As a base airfoil for the development of thick airfoils DU 97-W-300 was designed. Design goals were:

- A $C_{l,max}$ of 1.5 to 1.6 at R=3x10^6
- Location of maximum thickness around 30%c
- A thick trailing edge of about 1.5%c
- No lower surface turbulent separation at C_l=0
- Span wise position 40% (geometrical c/r about 0.18 to 0.20)
- Smooth transition to DU 91-W2-250
- Acceptable roughness performance (25% loss in $C_{l,max}$ accepted)

In figure 12 some pressure distributions are shown for specific angles of incidence in the lift-drag curve.
The measured performance of the airfoil both in the

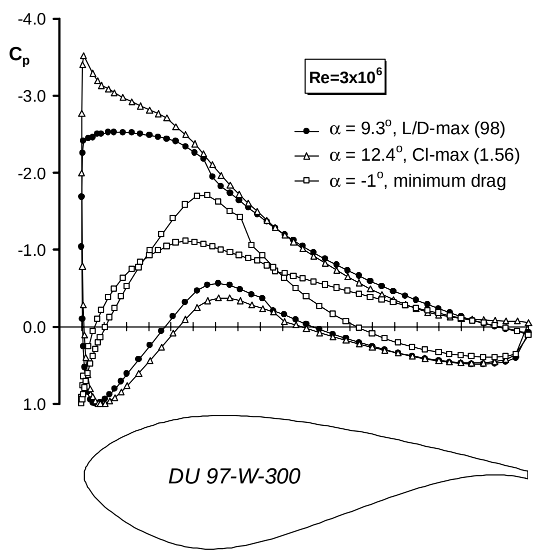

Figure 12: Measured pressure distributions for airfoil DU 97-W-300 at R=3x10^6

transition free and fixed conditions is shown in figure 13, for a Reynolds number of 3x10^6.
It was noticed that RFOIL tends to over predict the effect of the trailing edge thickness on the lift curve. Taking half the trailing edge thickness, will better represent the effect of a finite trailing edge on the lift curve. This was also confirmed by calculations for other airfoils.

Figure 13 demonstrates the effect of zigzag tape on the airfoil performance. The 0.35 mm thick zigzag tape at the 5% chord position reduces the $C_{l,max}$ from 1.56 to 1.16, which is considerable, but nonetheless acceptable for such a thick section. The sensitivity of the lower surface to roughness was investigated by locating 0.25

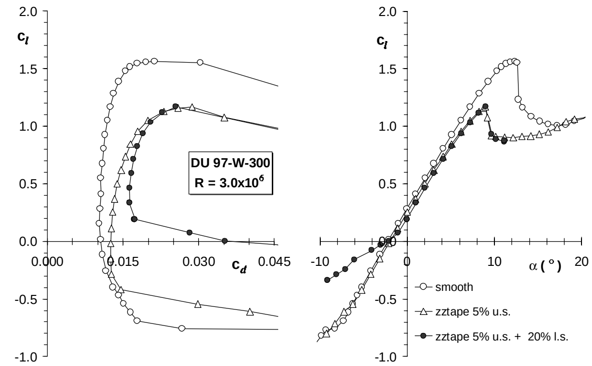

Figure 13: The effect of zigzag tape on the characteristics of DU 97-W-300 at R=3x10^6

mm thick zigzag tape on the lower surface 20% chord position as well. At negative angles the tape causes separation in an early stage, as indicated by the rapidly increasing drag and decreasing negative lift coefficient.

Figure 14 presents the RFOIL prediction for the smooth configuration and for the situation with zigzag tape on both surfaces. In the smooth case the maximum lift coefficient is well predicted. In the rough condition the $C_{l,max}$ is over predicted. In the calculation transition was fixed on 1%c upper surface and 5%c lower surface. It may well be possible that the earlier trip in the calculation (1%c) does not compensate for the increase in boundary layer thickness and momentum loss

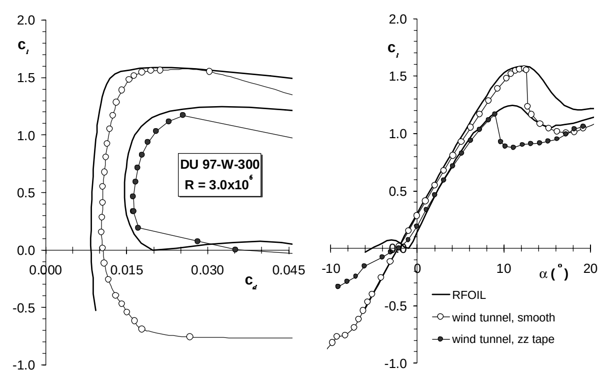

Figure 14: The measured and calculated performance of DU 97-W-300 at R=3x10^6.

thickness introduced by the 0.35 mm thick tape (at 5%c), in which case the boundary layer on the wind tunnel model is much thicker and will separate at a lower angle. In both cases the measured post stall lift curve drops more abrupt than is predicted. This may be caused by the 3-D flow pattern on the model just after stall of which the time averaged pressure distribution only gives local –and in this case too pessimistic- information. The predicted separation on the lower surface also starts at angles below 0^o, but the associated

effect on lift is more pronounced.
This behavior at negative angles is an indication that the thickness of the lower surface is pushed to the edge of what still is acceptable in terms of two-dimensional airfoil performance.
The problem of lower surface separation could be slightly alleviated by shifting the maximum thickness more forward. This, however, is unfavorable for the location of the beam as well as for transition to the hub. Fortunately, thick airfoils generally do their work at the

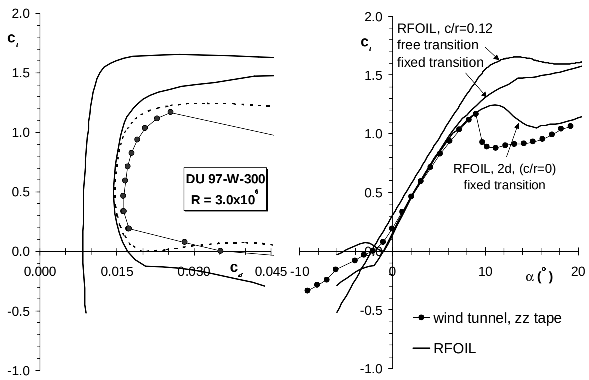

Figure 15: The RFOIL predicted effect of rotation on DU 97-W-300 in the transition free and fixed condition.

higher angles of attack and rotation helps the boundary layer to overcome a certain pressure rise.
Figure 15 presents the effect of rotation on the characteristics as calculated by RFOIL if it is assumed that the airfoil would be positioned at 40% radius (geometric c/r in the order of 0.19). The figure shows that at this radial position the lift keeps rising continuously in case of a tripped boundary layer. Calculations are performed for 2/3 of the geometrical c/r value. The lift characteristic at the negative angles is enhanced as well, although lower surface separation still comes in quite soon.

On the basis of the wind tunnel test on DU 97-W-300 and the RFOIL calculations for the 2d as well as the 3d configuration a number of thicker airfoils have been designed for various inboard positions taking rotational effects into account. Some blade manufacturers have different construction requirements with respect to trailing edge thickness and location of the maximum airfoil thickness, resulting in different sets of inboard airfoils. Of these sets recently DU 00-W-350 and DU 00-W-401 have been tested in the low-speed wind tunnel of the IAG Stuttgart, Germany [10]. The two-dimensional characteristics, both clean and rough, could be relatively well predicted by RFOIL.

THE EFFECT OF AERODYNAMIC DEVICES

Depending on the type of airfoil tested, during the wind tunnel measurements the effect of various aerodynamic devices such as Gurney flaps, wedges, trip wires and vortex generators (vg's) was evaluated.

Gurney flaps

Airfoil DU 93-W-210 was used to investigate the effect of Gurney flaps of 1%c (6 mm) and 2%c (12 mm), the effect of isosceles wedges of 1%, 1.5% and 2% height and of upstream length of the 1%c high wedges.
Figure 16 presents the effect of Gurney flaps of 1%c and 2%c on the characteristics of DU 93. The Gurney

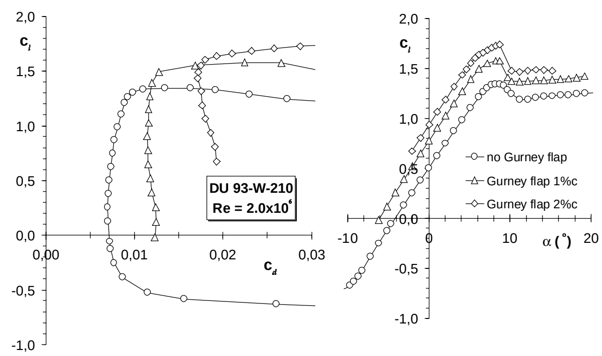

Figure 16: The effect of 1%c and 2%c Gurney flaps on the performance of DU 93-W-210.

flap was an L-shaped metal strip with a thickness of 2 mm attached to the lower surface trailing edge (see fig. 17). By the 1%c and 2%c Gurney flap the maximum lift coefficient was increased with respectively 0.24 and 0.40. The maximum lift to drag ratio, however, decreased from 136 to 117 and 89 respectively. Figure 16 is a typical example of the effect of 1%c and 2%c Gurney flaps, since the same trend was measured for DU 91-W2-250. It was concluded, and later on confirmed by others [12], that for these Reynolds numbers and airfoil shapes no increase of l/d max would result for Gurney flaps of 1% or higher. In fact, looking at the upper boundary of the low-drag buckets of the three curves on the left hand side of figure 16 it is even unlikely that the l/d will be enhanced by a Gurney flap smaller than 1%.

Trailing edge wedges

To gain more insight in the influence on drag of the separation bubble right in front of the Gurney flap, measurements were performed with 6x6mm., 6x13 mm. and 6x24 mm. wooden wedges, forming increasingly longer upstream fairings of the basic Gurney flap, see figure 17, giving a divergent trailing edge. The test results showed that there was virtually no difference between the characteristics for the 6x6 mm. wedge and

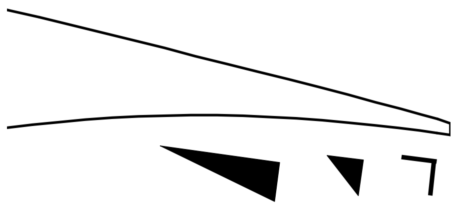

Figure 17: Sketch of the Gurney flap and some wedges applied to the trailing edge of DU 93-W-210

the 6 mm high Gurney flap. Apparently the 6x6mm wedge filled the space otherwise taken by the separation bubble in front of the Gurney flap. Further results are depicted in figure 18. It followed that with increasing upstream wedge length the maximum lift coefficient decreased while the maximum lift-to-drag ratio increased. The wedges with a longer upstream length have a smaller effect on the airfoil camber, but at the same time redirect the flow with less base drag.

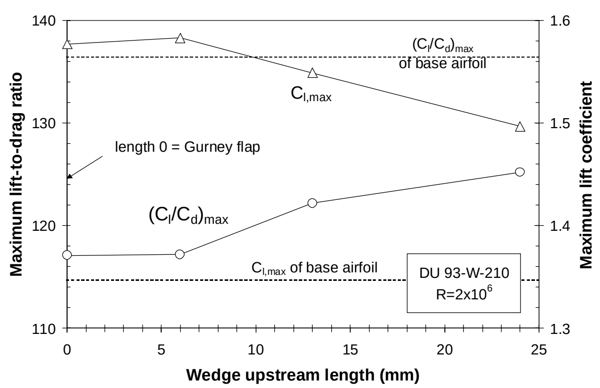

Figure 18: The effect of wedge upstream length on the $(l/d)_{max}$ and $C_{l,max}$ of DU 93-W-210.

A general conclusion from the tests with Gurney flaps on DU 93 and DU91 and from the wedge test on DU 93 is that Gurney flaps can be used to significantly increase $C_{l,max}$ at the cost of a fairly large drag increase. To minimize the negative effect on the maximum lift-to-drag ratio the flap height must be well under 1% chord. The result can be fine tuned by taking a wedge of the same height as the Gurney flap with increased upstream length.

Stall strips

Some wind turbine manufacturers tune the blades of stall machines producing too much peak power with stall strips, small metal strips glued to the blade nose to top off the lift performance of the outboard portion of the blade. In many cases a strip with limited length is enough to trigger the entire blade segment between the strip location and the tip. There was however some uncertainty about the proper location and the effect of thickness of the strip. DU 93 was used to do a wind tunnel test with trip wires on the nose of the model. Wires with 1.2 and 2 mm. diameter respectively were located at the apex (0%c) and at 0.25%c, 0.5% and 1% on the pressure side. Some results are presented in figure 19.

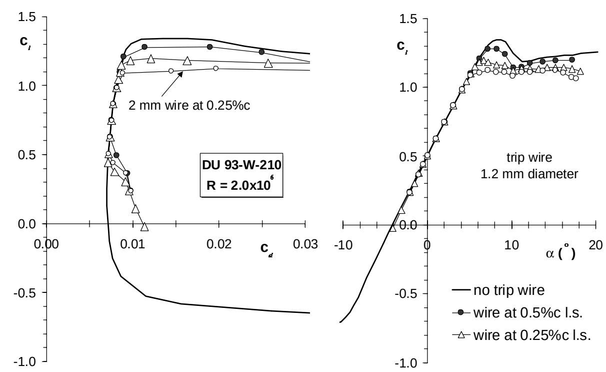

Figure 19: The effect on performance of thickness and location of a trip wire located on the leading edge of DU 93-W-210

The measurements show that the 2 mm thick wire at 0.25%c efficiently tops off the maximum lift capacity of the airfoil, since the maximum lift coefficient drops from 1.34 to 1.12. The drag bucket is narrowed significantly. The thinner wire at the same location is not so effective and results in a wider bucket. If the 1.2 mm wire is located at 0.5%c the bucket width remains the same as at 0.25%c but it shifts upward to higher lift coefficients along the drag curve of the base line airfoil. The effect on maximum lift has become smaller. In general terms the effect of a trip wire can be summarized as follows:

- No effect as long as the wire is in or very near the stagnation point
- The thicker the wire, the narrower the drag bucket
- The more aft located, the smaller the effect on the maximum lift coefficient.
- The range in chord positions for effective application of the trip wire is very small

Vortex generators

Blades for stall-controlled machines with moderate twist are generally equipped with vortex generators (vg's). For the prediction of power curves the effect of vortex generators was studied on all airfoils tested except DU 95 and DU 96 since these airfoils were meant to be in the outboard section of the blade. The

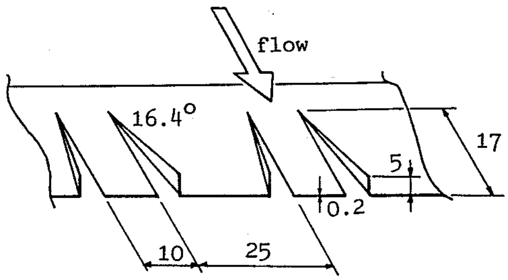

Figure 20: Sketch of the vortex generators used during most wind tunnel tests. Dimensions in mm

type of the vg has always been the same and resulted from a literature study and wind tunnel test in the late eighties. The type is sketched in figure 20 and is optimized for the 20%c and 30%c chord positions of 0.6 m chord models. It closely resembles one of the types investigated by Wentz [13]. Vg's are known to energize the boundary layer, helping it to overcome adverse pressure gradients. The result is suppression of trailing edge separation and consequently the delay of the stalling process of the airfoil. The type shown above proved to be very effective, and has been applied in

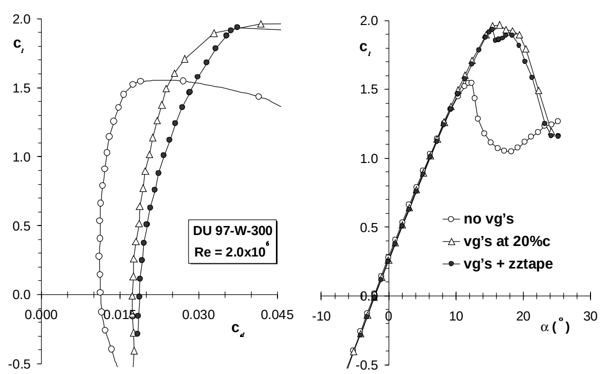

Figure 21: effect of vortex generators on the performance of DU 97-W-300 with and without zigzag tape

practice with success. In figure 21 an example of the test results is shown on airfoil DU 97-W-300. The drag measured with the wake rake showed a regular wavy pattern in span wise direction corresponding to the vane positions. The presented drag is an average value.
The vortex generators placed at 20%c increased the maximum lift coefficient of the base airfoil from 1.55 to 1.97. The mixing process, introducing vortices into the boundary layer, increased the drag considerably, which however due to the limited radial position of inboard airfoils will have little effect on the rotor torque. It is worth noting that the effect of premature transition, triggered by zigzag tape at 5%c, has little effect on the maximum lift. Apparently the boundary layer thickness did not grow fast enough to make the vg's work less efficient. The effect of rotation at the very inboard stations has a similar effect on the boundary layer. This is also an indication that in the design of thick inboard airfoils roughness (in)sensitivity requirements can be alleviated considerably.

LEADING EDGE SEPARATION ON WIND TURBINE AIRFOILS

At positions around 70% to 80% radius the flow over the blade behaves more or less two-dimensional. Dynamic effects may cause leading edge separation, which by some researchers is linked to multiple-stall levels of a rotor. In this light it was investigated if -with the available test data- the angle of attack at which leading edge separation would occur in the static situation could be predicted.
Figure 22 presents the measured lift curves of DU 96-W-180 and DU 97-W-300 at a Reynolds number of $1x10^6$. The sudden drop in lift at 23.4° (DU 96-W-180) and 35° (DU 97-W-300) is associated with the collapse of the negative pressure peak at the leading edge of the airfoil as a result of the separation process. The angle for leading edge separation (deep-stall) and the length of the hysteresis loop of the two airfoils differ considerably. In figure 23 the available data have been correlated with the thickness of the airfoil nose, defined

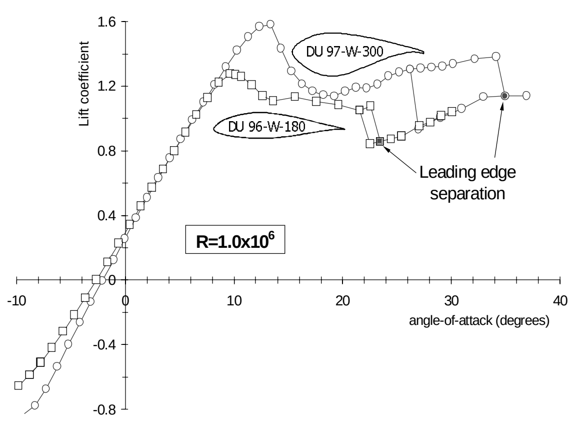

Figure 22: The lift curves of two DU airfoils showing leading edge separation

as the y/c value at x/c=0.0125, following the work of Gault [14], in which the stalling characteristics of a large number of low-speed airfoils have been correlated. Because the S809 model in the Delft tunnel was not driven into deep-stall, the S809 data point has been derived from OSU tests corrected by –0.5° to match the Delft lift curve. Negative values in x/c denote lower surface ordinates. There seems to be a linear relation between the thickness of the nose and the deep-

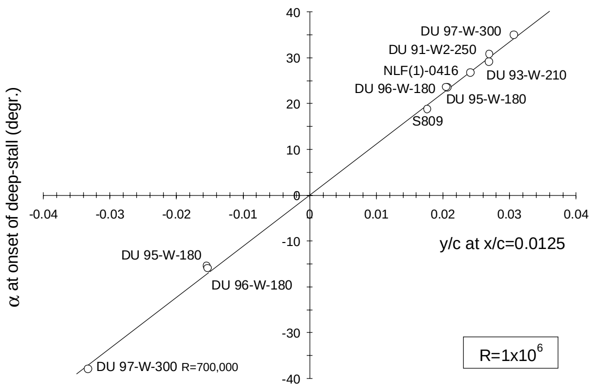

Figure 23: Correlation of deep-stall angle with leading edge thickness for a number of wind turbine airfoils

stall angle. Since the relation should also apply to symmetrical airfoils the curve essentially goes through the origin:

$$\alpha_{deep\text{-}stall} = 1114*(y/c)_{x/c=.0125} \qquad (2)$$

CONCLUDING REMARKS

The results of wind tunnel tests on 5 Delft University airfoils for wind turbines with thickness ranging from 18%c to 30%c have been presented. Primary design driver was low sensitivity to roughness. The effects on airfoil performance of Gurney flaps of 1%c and 2%c, of trailing edge wedges with various upstream lengths, of trip wires of 1.2 mm and 2mm thickness at various leading edge locations and of vortex generators was evaluated. The code XFOIL was modified to ameliorate lift predictions around stall and to calculate the effect of rotation on airfoil performance. The modified version is called RFOIL. It was used to design thick inboard airfoils with 30% and 40% relative thickness. The data base of wind tunnel results enabled the correlation of the angle for leading edge separation with the leading edge thickness in terms of y/c at x/c=0.0125. This relation appears to be a straight line.

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