Reynolds Number Effects on Thick Aerodynamic Profiles for Wind Turbines

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Introduction

In [1] Schewe reported $C_l(\alpha=12^\circ)$ measurements as function of Reynolds number (RN). A strong Lift-decrease was observed when going to RN above 3M on GROWIAN’s FX77-W-270 profile (see fig.1).

![Figure1](clrn.png)

Flow on wind turbine blades of length more than 50 meters may reach RN up to 12 M. As a consequence the whole design may be influenced strongly, if comparably negative RN effects are present. More detailed experimental and theoretical investigations and possible confirmation of these phenomena were carried out for a modern wind turbine profile: (a) measurements in Cologne’s Cryogenic Windtunnel (KKK) [2] and (b) CFD investigations with a 2D compressible Navier-Stokes solver in interaction with a differential boundary layer-code [6]. This article presents a preliminary and somewhat arbitrary summary of the work done so far. A more complete account will be published elsewhere.

Part A: Experimental investigations

The aerodynamic performance of a specific profile was investigated in the KKK in the RN range from 1 to approx. 10 millions. Cooling down the whole wind tunnel by injection of liquid nitrogen lowers the viscosity significantly. Therfore RN can be increased by a factor of five using the same wind speed (see fig.2).

![Figure2](rn-mn.png)

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drilled perpendicular to the surface. From the $C_p(x)$ distribution lift and torque was calculated by integration.

It is clearly seen that the design is mainly based on Delft’s DU-series \cite{7a, 7b} and is called DU300-mod.

**Experimental setup**

First the aerodynamic performance of the clean airfoil was measured. Then tripping wires at $x/c = 0.15$ and 0.30 were used for fixing the transition to turbulent flow at these specific locations. Finally Karborundum 60 and 120 (solid grains of 0.25 and 0.125mm, resp.) were used to simulate surface roughness close to the nose. This approach is somewhat different from the usual zig-zag-type roughness \cite{7b} but is rather common in airplane industry for modelling e.g. icing.

Finally aerodynamic devices like gurney flaps and vortex generators were added to determine the potential of possible lift improvement in these situations. A set of 125 pressure distributions and polars in total was received.

**Summary of experimental results**

(i) **Clean configuration**

A comparison with measurements done in the Delft university (TUD) wind tunnel \cite{7b} shows good agreement. All $C_l(\text{max})$ data fit to each other when RN (incl. MN) is increased. However, the Delft measurements show a somewhat steeper descent after stall (fig.3).

The zero-lift AOA and lift-slope curve agree to a surprising extend. Especially, if it is taken into account that the model construction as well the wind tunnel measurements were carried out completely independent.

![Figure 3: KKK measurements of the clean configuration compared with those of TUD \cite{7a,7b}. MN and RN is varying.](image)

(ii) **Configurations with increased surface roughness**

For the airfoil with increased surface roughness the present results differ significantly more from the TUD results. The TUD $C_l(\text{max})$ is close to 1.2 and $C_d(\text{min})$ close to 0.015. These values agree with the present results of tripped transition at $x/c = 0.15$. $C_l(\text{max})$ for the profile exposed to Karborundum roughness is only about 0.8 and $C_d(\text{min})$ in the order of 0.02 with a very thin ‘laminar nose’ around zero AOA. A striking feature is the early and strong trailing edge separation when reaching negative AOA below -1 deg. (see figs. 4 and 5).

![Figure 5: Comparison of clean, fixed-transition and Karborundum roughness performance ($C_d$) (same conditions as fig. 4).](image)

**RN dependence**

As shown in fig. 6 neither $C_l(\text{max})$ (upper triangles) nor $C_l/C_d$ (scaled by 0.01, lower squares) show dramatic decrease with RN increasing up to 10 M. A linear least square fit shows a decreasing $C_l/C_d$, however. Therefore Schewe’s measurements \cite{1} cannot be confirmed in his pronounced manner.

$C_l/C_d$ decreases for the highest RN (10 M) down to 85, 20 % less than the maximum $C_l/C_d$ (110 at RN=3.5 M). This is mainly due to fact that drag increases from ≈ 0.011 to 0.013 while lift remains almost constant (1.18 vs. 1.14). A possible explanation might be an earlier transition due to the thinner boundary layer at higher RN.

A proper consideration of these effects may lead to new types of profiles more suitable for RN up to 10 M.

![Figure 6: $C_l(\text{max})$ (▲) and $C_l/C_d \times 100$ (■) as function of RN (in millions) (all MNs: 0.1 to 0.2).](image)
Part B: Numerical investigations

For the CFD investigations the FLOWer code, being developed during the MEGAflow project [5], has been used. Several 2D as well as 3D wind turbine applications have been successfully treated within the VISCEL project [4]. To predict the lift-to-drag ratio of an airfoil properly, the location where transition appears due to e.g. Tollmien-Schlichting waves has to be included. This was done for the FLOWer code by Krumbein [8].

This approach assumes initially laminar flow on the largest part of the airfoil. Then the pressure distribution after a certain number of iterations is used as input for a compressible differential boundary layer and stability code [6]. This code returns either a laminar separation point or a location where an infinitesimal small disturbance introduced at the point of initial instability has grown by a factor of $e^N$. Therefore, an $N$ has to be provided until fully turbulent flow is obtained in the further iteration process by switching the turbulence model on.

Usually an equation proposed by Mack is used to relate inflow-turbulence with $N$:

$$N_{in} = -8.43 - 2.4 \ln(Tu)$$

The upper limit of applicability may be reached when $N=0$, corresponding to $Tu=3\%$. It has to be noted that for wind turbines $Tu$ levels up to 30% are reported (however, it is not clear to the authors which range of frequencies for integration is used). Therefore, phenomena know from turbomachinery flow, like bypassing the TS-scenario to turbulent flow, may become important.

The turbulence model is important for the prediction of the point of turbulent separation which determines $Cl_{max}$ to a large extend. In the present version FLOWer uses either standard $k-\omega$ by Wilcox or an algebraic model by Baldwin-Lomax. The following results were generated using the $k-\omega$ model.

The experiments show some MN dependencies [13]. Since the FLOWer code was developed for aerospace applications compressibility is inherently included.

Profile definition and mesh requirements

Several classes of aerodynamic profiles used for wind turbine blades have been investigated, for a full account see [3]. For some older profiles like the FX66-S-196 or the FX77-W-270 unphysical oscillations were initially found in the pressure distribution. These oscillations influenced the location of transition significantly. Obviously the set of isolated points describing the profile was inaccurate. To include all given points a curvature smoothing algorithm was used, which provided much smoother results.

For the computational mesh extensions common in 2D airfoil CFD were used. 10 chord length in all directions usually were found not to influence the final results. The mesh resolution in circumferential ($i$) and normal ($j$) directions was

$$i = 360 + 40, \quad j = 80$$

$$N = 32000$$

$$\Delta y_+ = 1...50 \cdot 10^{-4} \quad (\rightarrow y^+ < 2)$$

First the results of Krumbein [8] for the NLF(1) 0416 profile designed by Somers were reproduced. They are in close agreement with experimental data [12].

Wortman Profiles: FX66-S-196, FX77-W-270

Both profiles were chosen from the “Stuttgarter Profilkatalog” [9]. The first one – designed for sailplanes – was also investigated by a Danish Group(DG) from DTU and Risø [10a,10b].

In fig. 8 the measured and calculated transition location as function of angel-of-attack (AOA) is shown. The value of $N$ was chosen to be 9, as in [10a]. Good agreement between numerical and experimental results is obtained. The same applies to the lift and drag data (fig. 9).
Fig. 10 presents the shape of GROWIAN profile FX77-W-270. To obtain the appropriate form for the C-type topology of the block-structured mesh a finite tail was applied. This profile was experimentally investigated in a high pressure wind tunnel [1], where severe lift-decrease occurred for RN>3M. So far (fig. 11) the presented calculations do not confirm these results, even if massive surface roughness is taken into account by modifying the boundary values for specific dissipation rate.

DU300-mod

From the experimental data the transition locations of the DU300-mod profile, see fig. 12, can be derived for some low RN cases. CFD results are in good agreement with experimental data for the lower part of the considered RN regime. Best agreement was found for high values of N e.g. N=11 (fig. 13). According to (1) this corresponds to low inflow turbulence as expected for the experimental setup. Calculated drag forces are slightly higher than the measured ones. This tendency does not change, even if the e5 transition prediction method is completely deactivated so that turbulence onset is purely determined by laminar separation. The simulations yield too high lift coefficients (except in cases of low N values which are contrary to the transition locations). This might be caused by insufficient turbulence modelling. The calculations predict moderately positive effects for lift and drag forces with increasing RN, although the transition location moves upstream. A slight gap emerges between calculated and experimental data if RN is increased while N remains constant. For higher RN lower values of N are needed to match the calculations with experimental results, as shown in fig. 15. The corresponding inflow turbulence...
rate according to Mack’s equation would be significantly higher than expected for wind tunnel conditions.

Figure 15: DU300mod: Lift and drag, Re=10.2M

The lift to drag ratio Cl/Cd reflects that best agreement to experimental data is obtained for high RN flow if low values for N are applied, while low RN flow requires a higher N (fig. 16).

Figure 16: DU300mod: Lift to drag ratio, Ma=0.15

Summary and Conclusions

A combined experimental [2] and numerical project [3] has been undertaken to investigate RN and MN effects on thick airfoil (based on DU-300) performance. Measurements in the KKK could not confirm drastic decrease in lift, Cl(max), as reported for FX77-W-270 [1]. This is in accordance with numerical simulations applying the Navier-Stokes code FLOWer. Nevertheless, the lift to drag ratio of the profile decreases with increasing RN.

In difference to the commonly used zig-zag-tape type to increase surface roughness Karborundum 60 (120) was applied. The measured aerodynamic performance, as Cl(max) and Cl/Cd decreases much more significantly compared to the clean configuration than it was reported before [7b] using zig-zag-tape.

Usually MNs below 0.3 are not known to cause pronounced compressibility effects. In contrast to that Cl(max) and Cd(min) variations appear when changing MN from 0.1 to 0.2.

The FLOWer code with eN transition prediction method has proven its suitability for low Tu calculations in a wide RN range. For none of the considered airfoils a negative effect with increasing RN was found. In the case of the FX77-W-270 this is in dramatic contrast to experimental results [1]. For the DU300-mod some differences to the experimental results appear at high RN. These effects have still to be investigated, including the validity of Mack’s formula for high Re.

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