HARMONISATION AND IMPROVEMENT OF ROTOR BLADE QUALITY CONTROL

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1. Abstract

The tolerances as applied by the rotor blade and turbine manufacturers for a finished blade were investigated, discussed and harmonised. Due to the influence of the rotor design, e.g. tip speed ratio, power control and blade sections used, general tolerances applicable for all blades are limited. The participants agreed on a minimum set of tolerances.

Blade section and mould coordinates at app. 0.71, 0.84 and 0.95 rotor radius were measured by DEWI at six blades and four types of serial produced 20m blades. The aerodynamic properties were simulated and compared to the reference blade section. For two blades the rotor power curve and energy output were calculated and compared to the reference blade. Possible ageing effects were investigated by measuring a one year old blade. The results show that today's aerodynamic blade quality is fair or even good. Nevertheless improvements are possible, especially in the leading edge region. The typical energy loss due to blade section tolerances seems to be 1-2%, based on the limited number of blades investigated. Recommendations for the rotor blade quality control have been derived from the discussion on rotor blade tolerances and the results of the blade sections measured.

Four 40m prototype blades of the NÄSUDDEN II and AEOLUS II wind turbines, that were built in the same mould, were measured by FFA. Blade sections and twist angles were directly measured at the turbine, using special equipment. Significant differences were found, compared to the intended airfoils, as well as between the four blades. Nevertheless the energy output is reduced by 1.5% only, the same result as above.

The influence of the blade manufacturing errors, including twist deviation and blade section shape errors, on the aerodynamic performance of a horizontal axis wind turbine has been simulated by CRES. The adopted numerical method is based on stochastic analysis and standard blade element theory. It is shown that the standard deviations of the rotor power and thrust coefficients are proportional to the standard deviations of the introduced error on the twist angle and the aerodynamic parameters employed. The latter are defined by parametrizing the characteristic lift and drag curves of the blade sections. The global effect on power production and blade loading can be obtained through the linear superposition of the individual effects, as long as the introduced errors are small.

2. Partnership

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3. Objectives

An efficient and well defined quality control becomes more and more important in today's mass production of wind turbine rotor blades. The quality control procedures and manufacturing tolerances must be based on realistic requirements concerning the intended properties and economy of the rotor blades. Poor manufacturing quality of the blade profiles or twist distribution will affect power performance and noise emission. The project aims at identifying and avoiding such problems and will give recommendations and guidelines on the quality control of rotor blades. The project also aims at drafting improved and commonly agreed on quality control procedures and measures for rotor blades which can be applied by the manufacturers as "house quality procedure" under ISO 9000 and EN 45000. It is a first step towards a European Standard for rotor blade quality control.
The objective of the blade section measurements is to identify shape deviations which cause unacceptable differences in the blades aerodynamic properties. The goal are rotor blades of as constant properties as possible, checked by a harmonised quality control procedure.

4. Rotor Blade Tolerances

This work concentrates on the quality control of finished rotor blades. The quality control of the manufacturing process is not taken into account, although such quality problems may be traced back from the final quality control. The results given here refer to rotor blades of about 20m length.
To avoid direct relation between the participating blade manufacturers, the applied quality control procedures and the blades measured, all results are presented anonymous and normalised. Hence a blade manufacturer can not be blamed for a specific quality defect recognised and be punished for supporting the measurements in the end.

Quality Control Recommendations

- Absolute limits may apply for the blades natural frequencies.

- The blades of a blade set should be balanced within a tolerance of $\pm$0.5% of the mean mass moment at the blade root.

- The blade mass should be within $\pm$5% of the mean blade mass of the blade set. An absolute limit may apply.

- The rotor blade zero degree mark should be given within a tolerance of $\pm$0.2°. The reference blade section must be specified.

- The blade flange should be perpendicular to the blades radial reference axis within a tolerance of $\pm$0.15°.

5. Investigation of Six Serial Produced 20m Rotor Blades of Four Types

Rotor blades coming from the same mould do not necessarily show identical properties. The blades are more or less unique especially at the leading edge because the finishing work is done manually here. This is partly due to the alignment of the leading edges when finally gluing the upper and lower shell of a blade. The resulting leading edge shape depends on the skill, knowledge and motivation of the craftsmen. This finishing process can easily affect the stall behaviour of the blade and hence the maximum rotor power of a stall limited rotor.

Method Applied

Blade sections of a mould and a new blade from this mould were measured at about 0.71, 0.84 and 0.95 rotor radius, corresponding to 50%, 70% and 90% of the rotor swept area. The aerodynamic properties were simulated and compared to the reference section. It is assumed that the blade section measured is representative for the vicinity of this section. The results provide information on existing section shape deviations.
For two blades measured a rotor simulation based on this results was performed to analyse the differences in the power curve and the energy production.

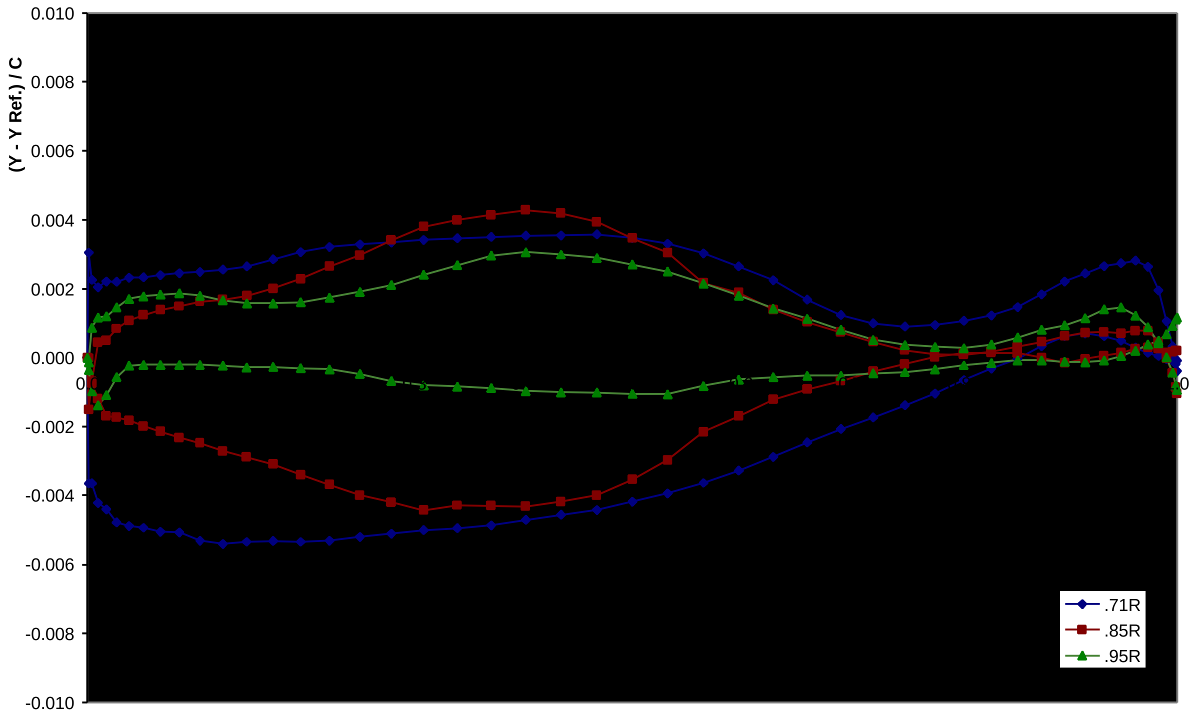

Fig. 1: Blade B, Y- Coordinate Differences

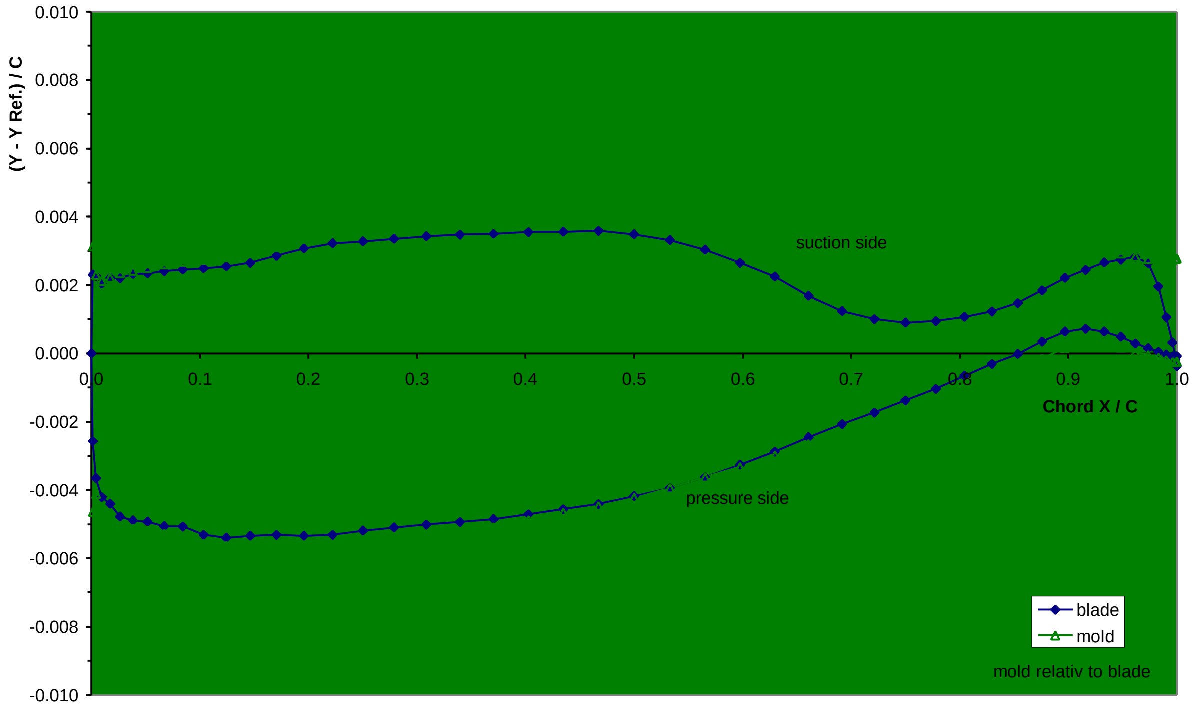

Fig. 2: Blade B, 0.71R Y- Coordinate Differences

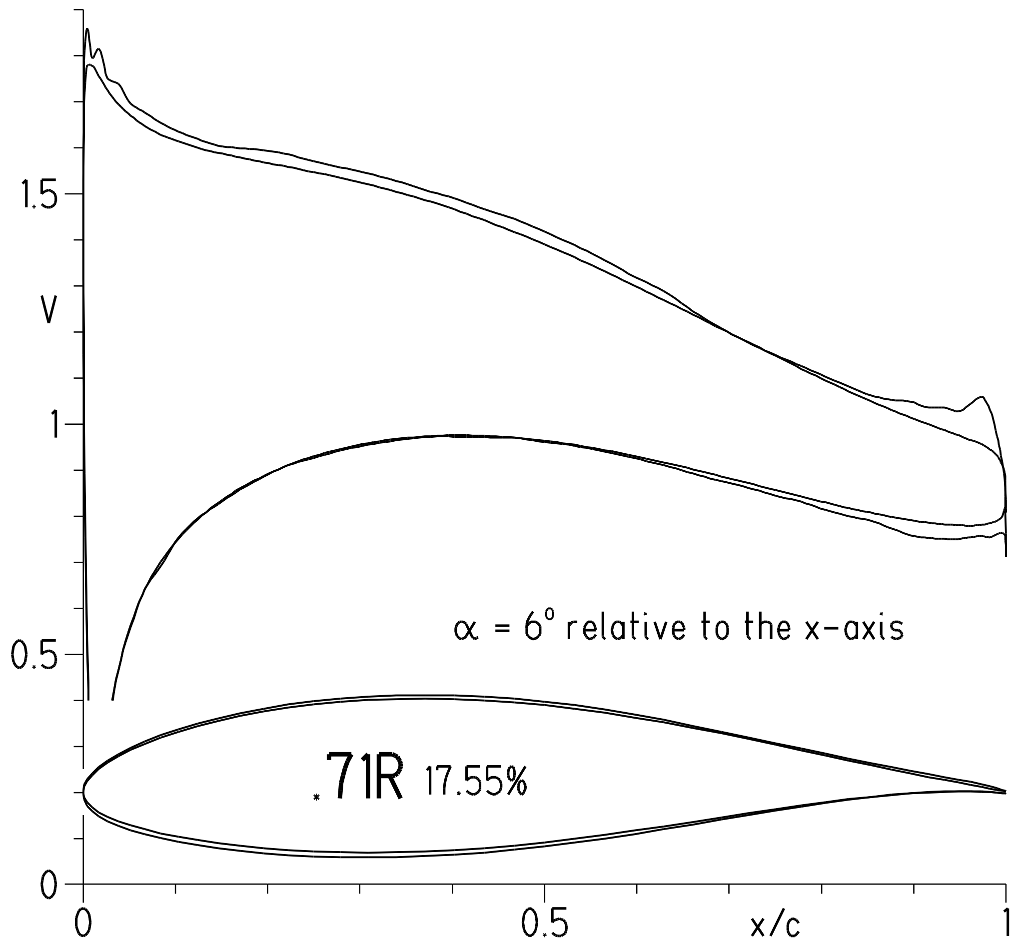

Fig. 3: Blade B, 0.71R velocity distribution compared to the reference

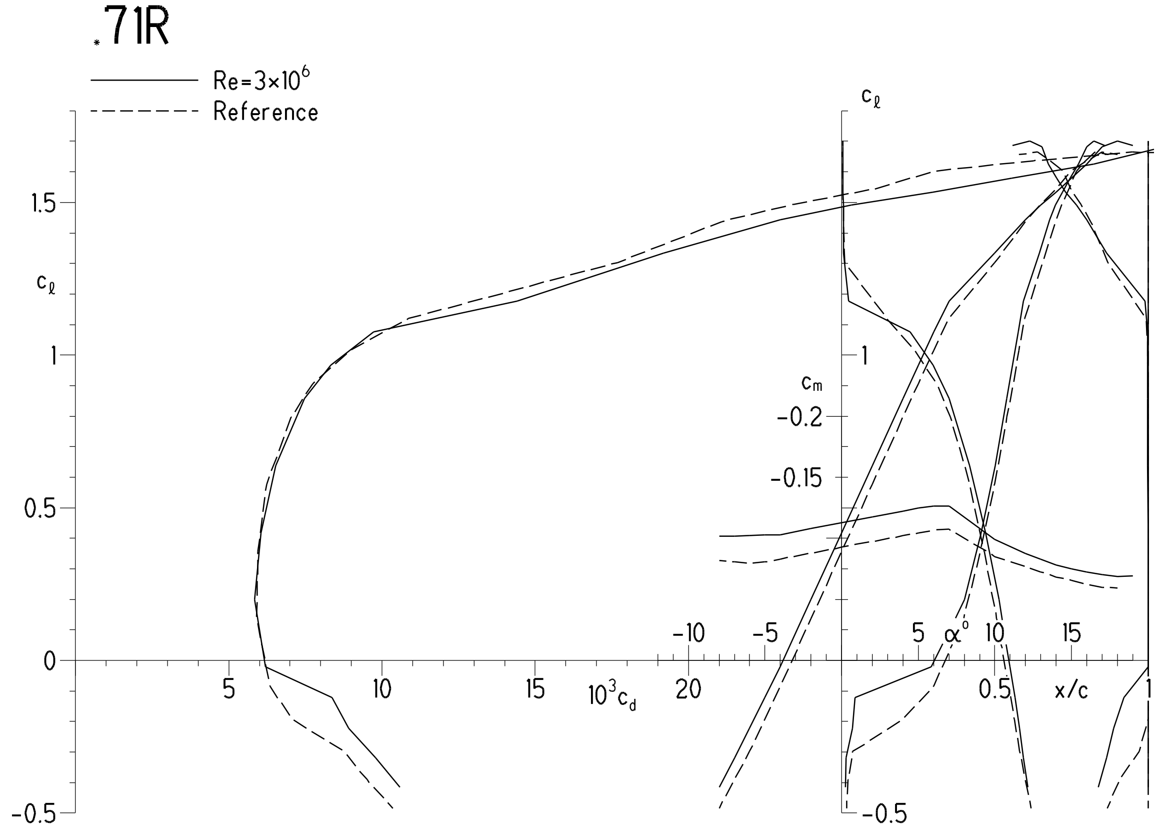

Fig. 4: Blade B, 0.71R aerodynamic coefficients

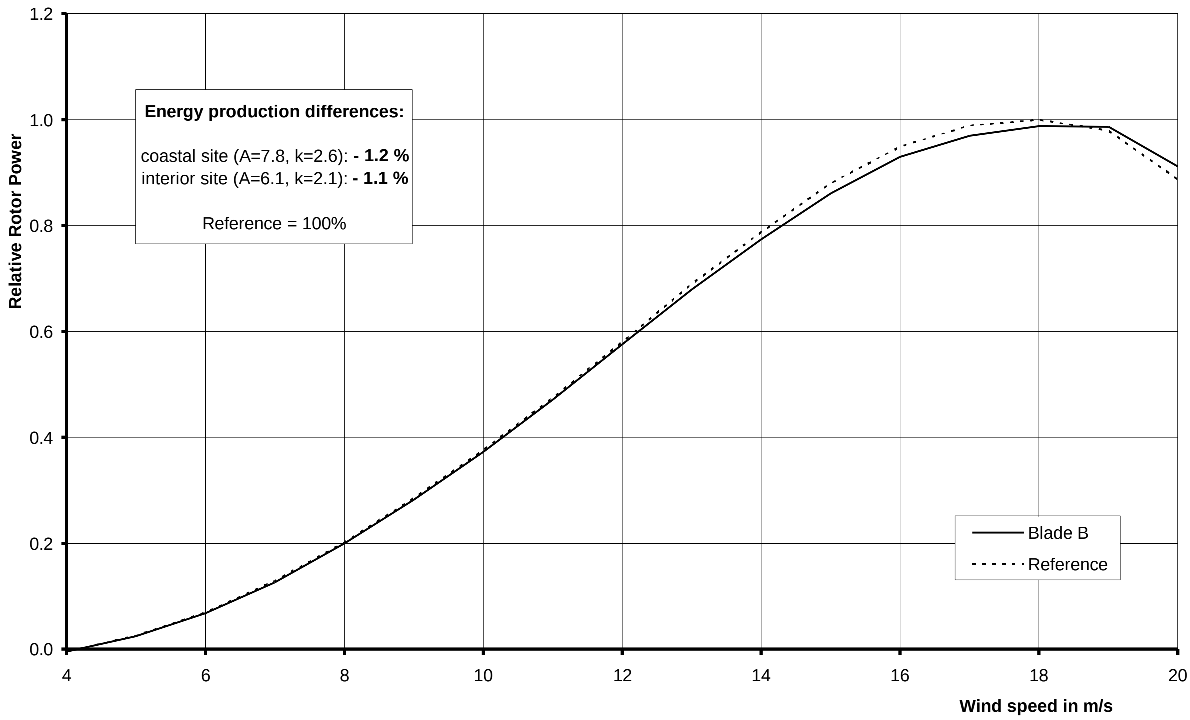

Fig. 5: Relative rotor power and energy production of rotor B

6. Airfoil Geometry Measurements at the Näsudden II and Aeolus II Wind Turbines and an Analysis of the Aerodynamic Characteristics of the Measured Airfoils (FFA)

6.1 Background

Carrying out research within the field of wind energy implies setting up priorities. Thus, certain assumptions have to be made and one such extremely common assumption is the acceptance of a specified blade geometry and its stated aerodynamic properties. What are the consequences if an actual airfoil geometry differs from the intended? What if individual blades on a turbine are not equal enough from an airfoil point of view?
In order to measure the geometry for later use in computational codes one either has to take an impression of the actual cross section and digitalize the imprint or measure the geometry directly. The latter method was chosen for this project.

6.2 Measuring Equipment

A SONY digiruler system was chosen for the measurements. Its basic component is a magnetic scale which can be applied to, for example a measuring frame. A detector of type PL23, which emits quadrature signals as it is being moved along the magnetic scale, was connected to counters on an NB-MIO-16 AD-board from National Instruments. The resolution of this system is 40 µm. The software environment used was LabVIEW on a Macintosh II ci computer. The measuring frame was assembled using a SEP-RO aluminium profile of dimension 50 by 100 mm. The aluminium girders were put on a flat table in the workshop and were found to be straight to within 0.1 mm over 3 m length when unloaded. An early intention was to use a laser and a pentagon prism to correct any deflection caused by exterior loads. However, this idea had to abandoned for both time and cost reasons and the applied solution was to visually inspect the girder for any significant deflection.
A measuring slider riding on the girder was constructed and manufactured at FFA.

6.3 Energy Production

The energy production of the rotor was calculated for each of the four blades measured and for the ideal blade, assuming that in each case both blades are identical. The simulated aerodynamic properties of the measured airfoil geometry's were input to a blade element model of the rotor. For this comparison a Näsudden II alike two- speed operation (14 rpm switched to 21 rpm at 9m/s) and a Rayleigh wind speed distribution are assumed. The rotor is operated at a pitch angle of 2°. The results were compared to the ideal blade idbl at 0° pitch angle, which is set to 100%. The Näsudden II blades refer to n2b1 and n2b2, and the Aeolus II blades to a2b1 and a2b2.

	ALFA	CL	CM	CD	S_{TR}	P_{TR}
FX 84-W-150	6.000	1.1456	-0.102	0.00764	0.285	0.869
N2_201_blade_1	6.000	1.1454	-0.099	0.01015	0.096	0.900
N2_201_blade_2	6.000	1.1378	-0.101	0.01079	0.057	0.900

Fig. 6: Example of pressure distribution at r/R=95%

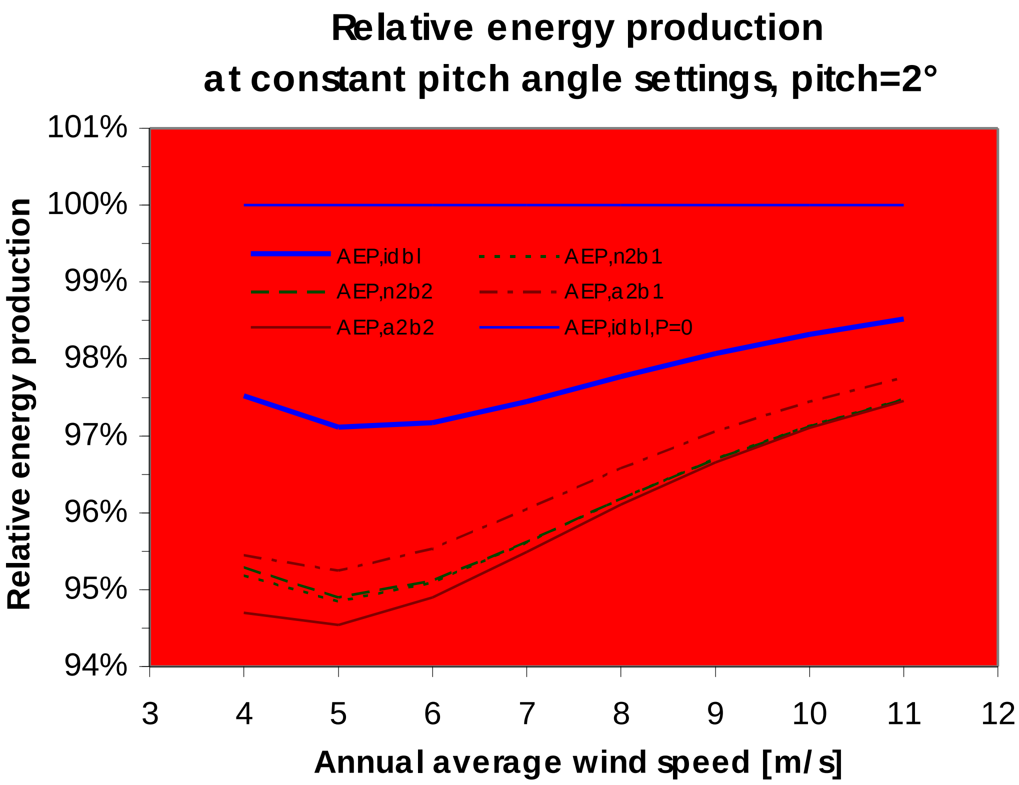

Fig. 7

7. The Influence of Blade Geometry Errors on the Performance of a HAWT (CRES)

7.1 Description of the Numerical Method

The aerodynamic code used for the calculations is based on the standard blade element theory. A new feature in the employed code is the use of a specific non linear solver that offers improved convergence characteristics, compared to the traditionally used secant methods.

The influence of the blade twist error on a horizontal axis wind turbine (HAWT) operation is investigated stochastically by introducing a Gaussian error on the twist angle at each blade section. Then, the deviations of the power C_P and thrust C_T coefficients, which characterise the rotor performance, are expressed as functions of the introduced error over the complete range of machine operation.

In order to quantify the effect of the geometry errors of the blade sections, the drag and lift curves of each section are parametrized using 10 aerodynamically meaningful entries. The influence of these parameters on the performance of the HAWT is then investigated. The different kind of systematic manufacturing errors (i.e.: leading edge curvature, section thickness, etc.) are associated to the variation of the introduced parameters and their effect on the HAWT operation can thus be estimated, through the same stochastic procedure introduced for the twist error.

The wind turbine used as ‘test-bed’ for the calculations is the Nordtank 500/37, with a calculated annual energy production of 1,613,958 kWh when operating at a site characterised by Weibull distribution constants k=1.8 and C=8.8m/s (typical windy Greek site). All the results presented below, unless otherwise stated, concern this particular machine-site setup.

7.2 Blade Twist Error

On each blade section, having a ‘design’ twist angle θ, a Gaussian distributed random error $\Delta\theta$ is introduced and the resulting power and thrust coefficients are calculated over the complete range of machine operation. One thousand realisations of perturbed twist distributions are performed for various σ_θ values. It appears, as expected for small changes, that the calculated C_P and C_T have also Gaussian probability distributions, which can be defined by their mean values and standard deviations. It also appears that, the standard deviations of the aerodynamic coefficients are proportional to σ_θ for small σ_θ values.

A suitable form for presenting these results is by plotting the standard deviation ratios $\sigma_{CP}/\sigma_\theta$ and $\sigma_{CT}/\sigma_\theta$ as functions of the wind speed, see Fig. 8. Note that, the standard deviation of the HAWT's power coefficient (σ_{CP}) can be converted to standard deviation of the power production (σ_P) using the formula:

$$\sigma_{CP} / \sigma_P = ½ \rho A V^3$$

where ρ denotes the air density, A the swept rotor area and V the wind speed.

Consequently, when the blade twist error is known, an error estimate of C_P and C_T is provided from the $\sigma_{CP}/\sigma_\theta = f(V)$ and $\sigma_{CT}/\sigma_\theta = f(V)$ plots. It is noted that the thrust coefficient variation is rather high at pre-stall operation but decreases significantly after 12m/s for the specific machine.

Fig. 9 shows the effect of a twist error with σ_θ=0.4 degrees on the power curve of the Nordtank 500/37 wind turbine. The error bars correspond to $\pm 3\sigma_P$, leading to a 99% confidence level. An almost negligible effect is recorded on the wind speed range corresponding to the linear part of the power curve. This is due to the dependence of the power production P on V^3. On the contrary, when stall occurs, the twist error effect on power production becomes significant, remaining almost constant for higher wind speeds.

The estimated annual energy production variation for σ_θ = 0.4° (1.2° standard error) is ± 27,708 kWh, or ± 1.7%.

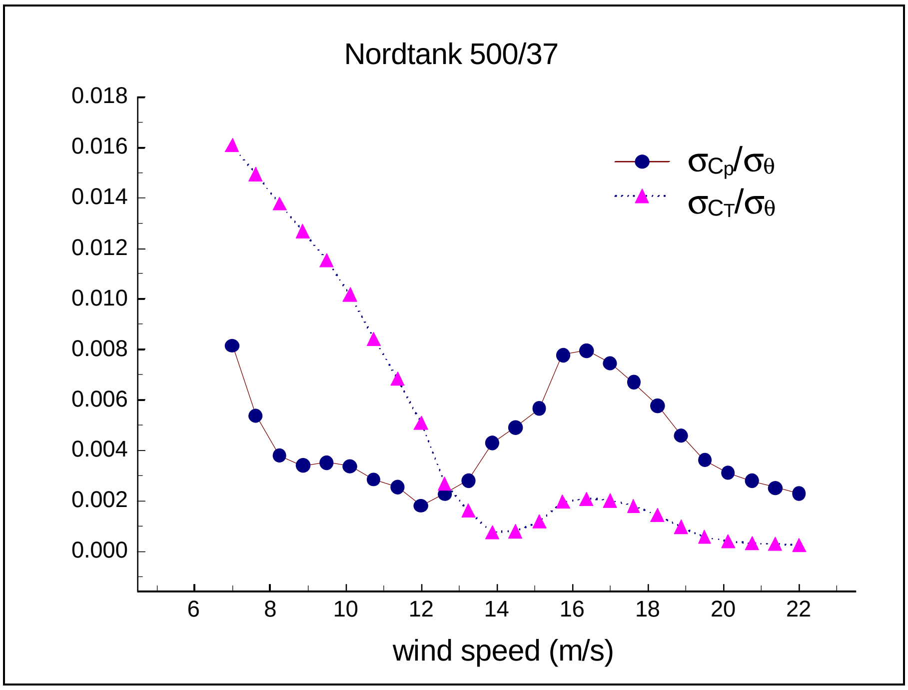

Fig. 8: Twist error effect on power and thrust coefficients.

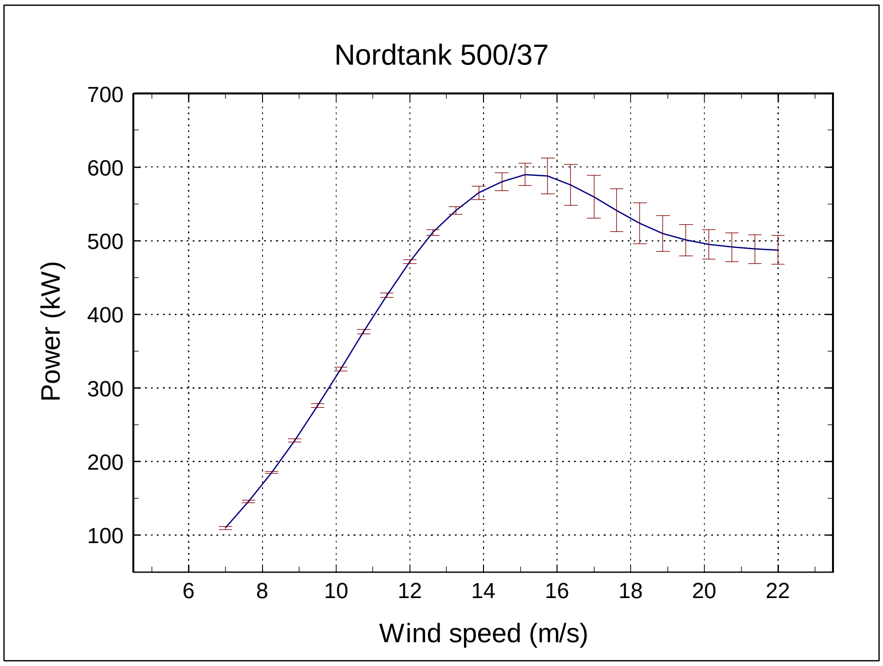

Fig. 9: Power curve uncertainty for a twist error with standard deviation $\sigma_\theta = 0.4^o$.

7.3 Thicker NACA 63-215 Section

Numerically, this case is treated by thickening the blade section, while smoothing its leading edge up to 0.025 chord c with a 5th degree polynomial, keeping the correct tangents on both, suction and pressure side of the blade and respecting the desired curvature. Being aware that, small deviations of the trailing edge shape may lead to disproportional change of the aerodynamic behaviour, the introduced error is linearly decreased to zero at the trailing edge region, beyond 0.9c.

Fig. 10 presents the variation of the aerodynamic parameters for the simulated geometry error. The CD(CLmax) parameter, the drag coefficient value at the maximum lift point, is the one mostly affected.

By introducing these trends into the aerodynamic data of the blade sections, one obtains the following percent variations of the maximum power and annual energy production for the above considered machine-site combination:

Maximum Power	+ 4.7 %
Annual Energy production	+ 1.8 %

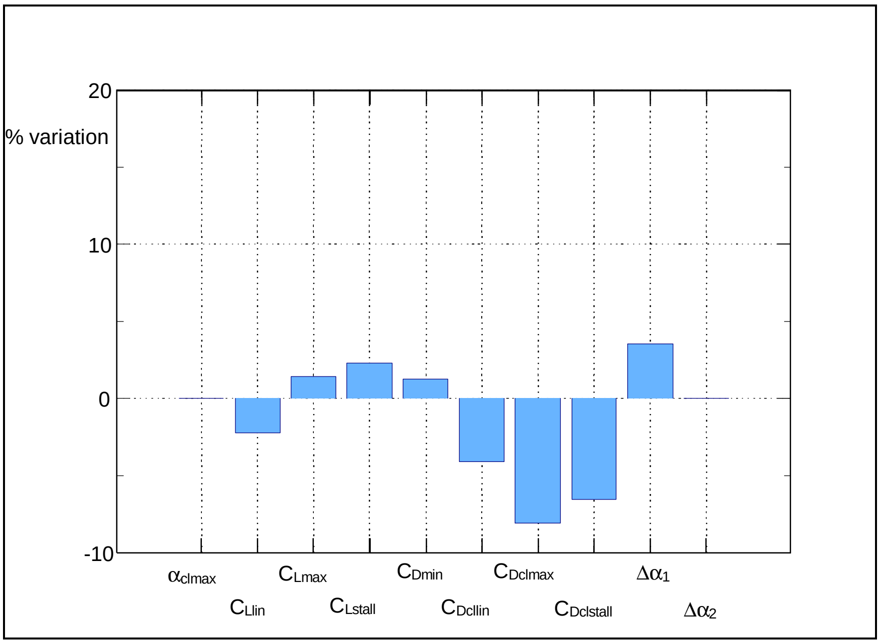

Fig. 10: Variation of the aerodynamic parameters in the case of a 0.4% thicker NACA 63-215 section.

8. Results and Conclusions

This work took advantage from a fruitful dialogue of project engineers, quality control engineers and research institutes. Only a few rotor blade tolerances could be harmonised, because it is not possible to define general tolerances e.g. for the blade section shape that do not depend on the rotor design.

The serial produced 20m blades investigated show generally a good aerodynamic quality. Except for one in four blade types, no unacceptable changes of the intended blade section properties resulted. The rotor simulations, done for two of the 20m blades measured here, show a rotor suffering from 16% overpower as the worst case. The calculated energy loss is 3% in this case for an interior German site, when the excess power is cured by a changed blade setting. The typical energy loss, compared to an ideal blade, seems to be in the range of 1-2%. The investigations further show that the section's changed aerodynamic properties can compensate more or less for each other in the blade's aerodynamic properties.

The results show that today's aerodynamic blade quality is good or at least fair. Nevertheless improvements are possible especially in the leading edge region. The leading edge joint is never perfect and has to be manually finished more or less. Unfortunately this region of the blade has a strong influence on the aerodynamic performance. At one section an increased leading edge thickness of 0.6% chord was successfully cured in the finishing process of the 18% thick section, without significantly changed aerodynamic properties. This is much more difficult at a section thickness <15% chord, having a smaller leading edge radius. Substantial overpower can result at a stall limited turbine using thin blade sections.

An increase of the section thickness of 1% chord seems not to be critical for the sections investigated here.
Thin trailing edges <0.5% chord can be manufactured, but only by additional finishing work. Originally they are mostly about twice as thick as planned and sharpened afterwards from the suction surface to contribute to a low blade noise.

Relative shape deviations, e.g. in percent chord, are effective for changes of the sections aerodynamic properties. Hence it should be possible to decrease the relative shape deviations at the even larger future blades, if today's absolute shape deviations can be reproduced for that blade size.

Conclusions

- Stall limited blades are more demanding than pitch regulated blades, concerning section shape deviations, because they have to keep a good power curve <u>and</u> the rated power limit.

- The most sensible region of a blade section, referring to shape deviations, is the suction surface close to the leading edge and the leading edge itself. It is hence recommended to use suction surface templates, extending from the leading edge to 15-20% chord.

- It is furthermore important to avoid waviness, especially in the above region, at the master blade (mould) and in the blade finishing process. Waviness can be easily detected by sliding ones hand in the flow direction over the section surface.

- Thick sections >15% are more forgiving for leading edge shape deviations than thinner sections are.

- It is recommended to seek the advice of an airfoil designer on the allowable tolerances of a specific blade section.

Airfoil Geometry Measurements at the Näsudden II and Aeolus II Wind Turbines and an Analysis of the Aerodynamic Characteristics of the Measured Airfoils (FFA)

The results of the four 40m prototype blades measured at the wind turbines Näsudden II and Aeolus II are similar to that of the 20m blades above.
The measured airfoil cross sections differ in some cases from the cross sections as presented in the final drawing of the blade. This is particularly true for the measured airfoils at 0.95R.

A deformed nose region was found on the suction side of one 0.95R airfoil, that effectively should prevent it from acting as a laminar type airfoil already at moderate angles of attack. Up to 0.5% more camber than what is expected, based on drawings, was measured. The effect is, that leading edge separation is prevented, i.e. a positive stall will more likely develop from the trailing edge rather than from the leading edge. However, the increased camber will cause positive stall to occur earlier than intended.

The twist angles are roughly 1° higher than what was expected at 0.95R. This means that the angle of attack also will be 1° less. If the change of twist was made intentionally, one reason might be to lower the loading of the tip in order to reduce noise. Another reason might be a wish to avoid positive stall.

For the four blades measured the mean difference in energy output is 3.7%, referring to the ideal blade at 0° pitch setting and an annual average wind speed of 8m/s. It is remarkable that 2.2% energy loss can be avoided by pitching the blade from the 2° used to 0°. That means that only 1.5% of the energy loss are due to the marked deviations from the ideal blade, which may be acceptable for prototype blades. The differences in energy output between the two Näsudden II blades are small, but for the Aeolus II they exceed 0.5 % under the above conditions.

The Influence of Blade Geometry Errors on the Performance of a HAWT (CRES)

The influence of the blade manufacturing errors, including twist deviation and blade section shape errors, on the aerodynamic performance of a horizontal axis wind turbine (HAWT) has been investigated numerically. The adopted method is based on stochastic analysis and standard blade element theory. It is shown that the standard deviations of the rotor power and thrust coefficients are proportional to the standard deviations of the introduced error on the twist angle and the aerodynamic parameters employed. The latter are defined by parametrizing the characteristic lift and drag curves of the blade sections. The global effect on power production and blade loading can be obtained through the linear superposition of the individual effects, as long as the introduced errors are small.

9. Exploitation Plans and Anticipated Benefits

The rotor blade investigation method as used by DEWI and FFA will be offered to blade and turbine manufacturers. It proved to be an effective tool for the aerodynamic quality control and allows to find and assess the most important flaws of a blade.

For an economic rotor blade production the blade section geometry should only be as accurate as necessary. CRES’ method to simulate the influence of isolated blade geometry errors proved to be a suitable tool to define tolerances for a specific blade design.