MODELLING OF ROTATIONAL AUGMENTATION BASED ON ENGINEERING CONSIDERATIONS AND MEASUREMENTS

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Abstract

For wind turbines the effects of rotation lead to larger aerodynamic power and thrust compared to predictions based on 2D aerodynamic coefficients, which has been the subject of investigation for decades. Most models that account for the effects of rotation are in terms of increased lift or delay of stall to larger angles of attack. A model is presented based on a description of the separated flow at the trailing-edge. It includes the effect of the local speed ratio and it also gives a correction for the drag. This approach led to a so-called ‘centrifugal pumping’ correction model for the normal force coefficient together with a delay of separation to larger angles of attack. The centrifugal pumping model gave a good fit to the lift and the drag coefficients from the NASA-Ames wind tunnel measurements, but does not yet describe the reduction of the coefficients at the tip and the strong increase of coefficients near the root.

A comparison is presented with predicted rotating aerodynamic coefficients for the UAE Phase-VI rotor of NREL, which was measured in the NASA-Ames wind tunnel in the spring of 2000. These comparisons also included the Navier-stokes calculations with EllipSys3D by Johansen (Riso). Although the ‘end effects’ were not yet included, the model presented here also deals with the drag coefficient.

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1 Introduction

Nowadays the inaccuracy of the design and analysis models (computer programs) for wind turbines is for a large extent due to the fact that aerodynamic blade loads (for a given wind load) have some uncertainty. In or near stall this uncertainty is dominated by the fact that rotating airfoils have far larger aerodynamic (lift-) coefficients than the non-rotating (or ‘2D’) coefficients.

Although the blades of modern variable-speed wind turbines are not in stall during normal power production, the fact that the design calculations include extreme wind speed variations and faults of the yaw or pitch controller may lead to temporary high angles-of-attack and thus requires realistic design models for the effects of rotational augmentation. This means that a good understanding of the effects of rotation is of eminent importance for the development of current generation large size wind turbines.

Previous investigations

In the 40’s Himmelskamp [11] investigated the increased (maximum) lift coefficients of rotating airscrew propeller blades which he addressed to the occurrence of radial flow. This increase in maximum lift is the strongest for the smaller radial sections while it was found that stall occurs at larger angles of attack than for the non-rotating state.

The effects of rotation have also been investigated intensively for helicopter rotors. These investigations consider among others the local oblique inflow of the rotor blades in forward flight, see e.g. Harris [10] who described the effects of rotation similar as for a blade operating in yawed flow. In addition to the conventional approach of calculating the aerodynamics with the flow component normal to the blade axis, a blade/wing in oblique inflow showed an increased maximum lift. In this respect a fundamental aspect of the stalled flow area in oblique inflow is that the axis of vorticity is not perpendic-
ular to the local flow direction and that the separation area is transported in spanwise direction and thus reducing the effect of stall. For helicopters in forward flight Dwyer & Mc Croskey [8] also gave a description of the effect of ‘crossflow’ on the rotor blades.

For the early stall-controlled (‘Danish’) wind turbines it had been noticed in the past that the aerodynamic power tends to exceed the design value, which since then became a design item. For the description of the rotational effects or ‘stall delay’ several models have been formulated, most of which are in terms of a correction to be added to the non-rotating lift coefficient. A few of these models also describe a correction (increase) of the drag coefficient. Some correction models for rotational effects are based on the mechanism of centrifugal pumping of air in the trailing-edge separation bubble. In [18] D. Milborrow reported on the conclusions by Harris [10] that ‘Most have suggested that stall is likely to be delayed by radial flows but few have attempted to analyse the turbulent boundary layer, and none appear to have quantified the magnitude of the increased lift’.

One of the first calculation models for wind turbines that included the effects of rotation was described by Sørensen in [22]. In the publication of his work, Sørensen showed flow fields with radial-flow patterns in the trailing-edge separation area. This was supported by later numerical investigations for the S809 airfoil [23], which clearly show ‘centrifugal pumping’ near the trailing edge. Later Eggers & Digumarthi [9] compared a model for rotational augmentation with measurements on the UAE Phase-II rotor with S809 airfoils.

2 Effects of Rotation on Flow

First the aerodynamic phenomena involved with blade rotation are described.

2.1 Driving Forces

For many airfoils used in aircraft and wind turbine engineering the non-rotating ‘2D’ aerodynamic coefficients are available, usually from wind tunnel tests. Compared to the flow in a wind tunnel, rotation of a rotor blade has the following effects:

- All volumes of air that rotate to some extent with the blade (boundary layer) are subjected to a ‘centrifugal load’ driving to larger radial locations. This holds for the boundary layer and for the separated flow areas.
- For a stalled flow, the radial velocities from the centrifugal effects require Coriolis forces in order not to leave from the trailing edge. This effect partly reduces the volume of the stalled flow area, and partly gives an increased suction on the airfoil.

It was found by Dwyer and Mc Croskey [8] that the influence of the radial pressure gradient has its largest effect on stall delay. Also the Coriolis-effects were found to be dominating over the centrifugal effects (although they are associated).

2.2 Leading edge suction peaks

In the cylindrical coordinate system attached to the rotating blade, the centrifugal loads act on all volumes of air of which the relative tangential velocity differs from $\Omega r$. This includes the inner boundary layer, the (laminar) separation bubbles, and the turbulent separation at the trailing edge. The centrifugal loads on the boundary layer and the laminar separation bubbles accelerate the air towards larger radial locations. In a rotating system, the air with radial velocity has a Coriolis force towards the trailing edge that has to be in equilibrium with a chordwise pressure gradient, see [6]. If this pressure gradient is insufficient or absent the air with radial flow (in the boundary layer or separation bubble) tends to leave at the trailing edge.

As a result of this mechanism the boundary layer moves slightly outboard and is less thick and more "stable" compared to the non-rotating state. In practice the formation of separation bubbles and leading edge stall is suppressed, which was also shown by the large leading-edge suction peaks observed by Barnsley & Wellicome [2]. The ‘delay’ or ‘absence’ of leading edge stall was also shown by Butterfield for the 80.0% section of the phase-II rotor (Figure 3 of [3]) giving a nearly constant rotating lift coefficient for the S809 airfoil, for angles of-attack where the non-rotating coefficients show a pronounced stall.

This means that depending on the airfoil, the aerodynamic coefficients first need to be found/corrected without formation of laminar separation bubbles or leading-edge stall. These ‘2D’ stall data can be obtained either: 1) for large Reynolds numbers or measurements with vortex generators, 2) from other airfoils with a similar after-body that have no L.E. stall.
2.3 Effects on drag coefficients

On basis of chordwise pressure distributions Himmelskamp [11] found an increased drag due to rotation. In [18] Milborrow concluded on basis of previous studies that for angles-of-attack above 5° the drag coefficients show an increase due to rotation. Milborrow also reports on the observations of Viterna & Janetzke [27] on basis of power measurements that the drag appears to be reduced. The measurements on the UAE phase-VI rotor in the NASA-Ames wind tunnel [16] finally give a serious increase of the aerodynamic drag coefficient.

The models that describe rotational augmentation in terms of delay of stall to larger angles-of-attack, inherently give a reduction (!) of the aerodynamic drag coefficients. The model for ‘stall-delay’ of Du & Selig [7] describes a reduction of the drag coefficient. However, by the fact that ‘centrifugal pumping’ of the separated flow requires energy, an increased rotating drag coefficient is expected.

Many but not all observations and models show an increased drag, from which it follows that there is no clear consensus on the effect of the drag coefficient. Knowing that the rotating sectional coefficients show a strong (local) increase towards the root and a strong (local) decrease towards the tip that deviates from most correction models the rotor shaft torque itself can not be used as basis for estimation/evaluation of the rotating drag coefficients. When using measurements for verification or as basis for modelling, one must be aware of the accuracy of the data, which was also the first conclusion of [18] by Milborrow. This holds in particular for the drag coefficient because integrating the tangential force from pressure-tap data itself is inaccurate and the decomposition into a drag coefficient is sensitive to small errors in the measured angle-of-attack.

3 Centrifugal Pumping model

The model described here is based on the effects of trailing-edge stall for which state the rotor acts as a ‘centrifugal pump’ on the separated volume of air. This model is in terms of a correction to be applied to the non-rotating coefficients. As explained in the previous section one always needs to have tables with aerodynamic coefficients from which the effects of leading-edge stall (and of leading-edge separation bubbles) are excluded.

At large angles of attack (in stall), the chordwise pressure distribution on the suction side of an airfoil has a large suction peak just aft of the leading edge and decreases towards the trailing edge. The magnitude of this suction peak is proportional to the ‘dynamic pressure’ so it increases roughly with the radial location squared. The span-wise gradient of the dynamic pressure and the chord-wise gradient of the negative pressure on the airfoil provide a mechanism by which the air in the separated area flows to larger radial locations and can overcome the Coriolis-loads. Klimas [14] described radial flow based on the Euler-equations including the centrifugal and Coriolis-effects on the flow in the trailing-edge separation bubble. Following Eggers & Digumarthi [9] and other publications this mechanism is called ‘centrifugal pumping’ in the remainder of this paper. It has also been reported as ‘radial pumping’ (Sørensen et al. [23]), ‘spanwise pumping’ (Harris [10]), or ‘spanwise flow’ (Klimas [14]). In recent years correction models based on the mechanism of ‘centrifugal pumping’ were formulated by Corten [6] in terms of a correction on the lift coefficients, while the correction method of Chaviaropoulos [4], also describes a linear (c/r) dependency.

For the ‘attached flow’ part the pressure distribution over the airfoil surface is proportional to the dynamic pressure of the relative airflow on the blade section. Because the trailing-edge side of the separated area of flow has a pressure that is close to the atmospheric pressure, the pressure from chordwise flow in this area has only a small spanwise gradient. This means that the separated volume of flow is subjected to a dominant ‘centrifugal loading’ (a force that appears to act in a rotating coordinate system) that is proportional to the local radius of the section. Assuming that trailing-edge stall appears over a large part of the blade span, it can be shown that the ‘centrifugal loads’ result in a radial velocity \( v_{\text{rad}} \) that is proportional to (theoretically equal to) the tangential velocity: \( v_{\text{rad}} = \Omega r \). If the separated area with radial flow follows the blade angular velocity \( \Omega r \) it needs a Coriolis-acceleration that is proportional to \( 2 v_{\text{rad}} \Omega \cos(\theta_w + \theta_p) = 2\Omega^2 r \cos(\theta_w + \theta_p) \).

The cosine of this angle is approximated by 1 because:

- In fact one should use the component of the Coriolis-effects in the direction of the upper surface of the trailing-edge of the airfoil, which is airfoil-dependent;
- The cosine of this direction only differs significantly from 1 if the sum \( (\theta_w + \theta_p) \) is large for which case either the airfoil is not in stall (small a.o.a.), or the local speed ratio is small which approaches the non-rotating conditions.

Expressing the size of the trailing-edge separation area in the dimensionless chordwise location of the separation point \( f \) gives \( \text{size} = c(1 - f) \). Assuming that the additional sectional load is proportional to this ‘size’ then the negative pressure
loading on the suction side of the airfoil due to the Coriolis-accelerations gives an additional normal force on the airfoil that is proportional to:

\[ f_{n,\text{rot}} - f_{n,\text{2D}} = \text{factor} \rho c \left(1 - f\right)^2 \Omega^2 r. \]

where \( \text{factor} \) is used for scaling of the correction. Corten used this suction force proportional to the square of the separation dimension \( (c(1 - f))^2 \) based on the triangular pressure distribution, [6].

Following common practice, the sectional aerodynamic loads are made dimensionless with \((\rho/2)(\Omega r + V_i)^2 + (U_{\text{wind}} - U_i)^2 = (\rho/2)V_{\text{eff}}^2\). Here \( U_i \) and \( V_i \) are the axial and tangential induced velocities. The increase of the dimensionless normal-force coefficient follows then:

\[ c_{n,\text{rot}} - c_{n,\text{2D}} = \text{factor} c \left(1 - f\right) \Omega^2 r / V_{\text{eff}}^2 = 1.6 \left( c/r \right) \left(1 - f\right) \left( \Omega r / V_{\text{eff}} \right)^2. \]

The 'scaling' factor 1.6 results from comparison with the measured shaft torque of the UAE phase-VI rotor, see section 5 or chapter 6 of [16].

Because this derivation is addressed to the rotating state, the tangential induced velocity \( V_i \) is small compared to the rotational velocity \( \Omega r \), so that the term \( (\Omega r / V_{\text{eff}}) \) can be expressed in the local speed ratio \( \lambda_i = \Omega r / (U_{\text{wind}} - U_i) \) so that \( (\Omega r / V_{\text{eff}})^2 \approx \lambda_i^2 / (1 + \lambda_i^2) \).

An approximation that is more practical for implementation is \( (\Omega r / V_{\text{eff}})^2 \approx \left( \cos \phi_{\text{inflow}} \right)^2 \) which finally gives the rotating force coefficient:

\[ c_{n,\text{rot}} - c_{n,\text{2D}} = 1.6 \left( c/r \right) \left(1 - f\right) \left( \cos \phi_{\text{inflow}} \right)^2. \]

The relation for trailing-edge separation \( f \) following the Kirchhoff/Helmholtz model (see also p.252 of [15] by Leishman) for the normal force coefficient is \( c_n = \partial c_{n,\text{pot}} / \partial \alpha \cdot (1 + \sqrt{f})^2 \cdot (\alpha - \alpha_0) \).

Here \( \alpha_0 \) is the angle of attack for zero lift.

**Shift in angle of attack**

The 'centrifugal pumping' effect on the separated volume of air near the trailing-edge, gives an additional negative pressure on the airfoil-surface. This additional negative pressure gives a negative chordwise pressure gradient which is favourable for the stability of the boundary layer, and may therefore lead to a shift of the separation point towards the trailing edge. This shift may be hard to model, but one may assume that equilibrium for the same location of the separation point is obtained for a larger angle-of-attack such that the chordwise pressure gradient, including the effect of the rotational augmentation, is the same as for the non-rotating state, see Figure 1. On basis of this relation the shift or delay in angle-of-attack can be derived. Related to this 'shift' in angle-of-attack, the lift coefficient has to be scaled such that it has the same ratio \( f \) between the curve for fully attached potential flow and the curve for complete separation.

The shift in angle-of-attack due to rotation is modelled with a similar relation as the rotating normal-force coefficient but without the size \( 1 - f \):

\[ \alpha_{\text{rot}} = \alpha_{\text{2D}} + 0.25 \text{rad} / (2 \pi) \cdot 1.6 \cdot \left( c/r \right) \cdot (\Omega r / V_{\text{eff}})^2. \]

The empirical factor 0.25 rad was based on the measurements on the UAE phase-VI rotor only. It is recommended to find a physical basis, or to assess this factor using more measurements. Here the difficulty is that the scaling of the shift in angle-of-attack relies heavily on the increase of the drag coefficient, which requires accurate measurements of the tangential-force distribution and an accurate tool to reconstruct the inflow angle. In order to overcome the latter aspect effort has been paid to a proper functioning of the vortex-wake based tool inflow that was used for analysis of the measurements on the UAE Phase-VI rotor in the NASA-Ames tunnel.

The increase in lift and drag coefficient are the \( \cos \alpha_{\text{rot}} \) and the \( \sin \alpha_{\text{rot}} \) components of the increase in normal force coefficient:

\[ c_{l,\text{rot}} = c_{l,\text{2D}} + 1.6 \cdot (c/r) \cdot (\Omega r / V_{\text{eff}})^2 \cdot (1 - f)^2 \cdot \cos(\alpha_{\text{rot}} - \alpha_0) \]

\[ c_{d,\text{rot}} = c_{d,\text{2D}} + 1.6 \cdot \sin \alpha_{\text{rot}} \cdot (1 - f)^2 \cdot (c/r) \cdot (\Omega r / V_{\text{eff}})^2. \]

In addition to the dependency of the speed ratio (also used by Du & Selig [7]), major differences compared to other models are:

- Increase of the \( c_n \) instead of \( c_l \);
- Delay in terms of \( \alpha \) related to the \( c_n \) increase;
- Includes chordwise dimension of T.E. separation.

It should be emphasised that a correction (partly) in terms of a delay in angle-of-attack is not likely to exceed the potential lift coefficients.

Basically the aerodynamic drag for the rotating state has a contribution from the fact that tangential momentum is fed into the separated volume of air with radial flow. It has not yet been investigated whether a term for the tangential momentum of the radial flow has to be added.

Figure 1: Non-rotating and rotating sectional flow
4 Other correction models

4.1 ”3D-correction” of Snel et al.

Snel, Houwink, and Bosschers derived a so-called ‘3D correction’ method [21] that gives an increase of the aerodynamic lift coefficient for the effects of rotation. Their correction model was proportional to \((c/r)^2\):

\[ c_{\text{rot}} = c_{\text{2D}} + 3.1 \cdot \left( \frac{c}{r} \right)^2 \cdot (c_{\text{pot}} - c_{\text{2D}}). \]

This model has been implemented earlier in the design codes BLADMODE and PHATAS, including the ‘local speed-ratio’ dependency such as derived on basis of ‘centrifugal pumping’ model:

\[ c_{\text{rot}} = c_{\text{2D}} + 3.1 \cdot \left( \frac{\Omega r}{V_{\text{eff}}} \right)^2 \cdot (c_{\text{pot}} - c_{\text{2D}}). \quad (2) \]

This correction has to be applied for locations up to 80% radius and for angles-of-attack up to 30°. For larger angles-of-attack the correction on the lift coefficient was reduced linearly to zero at a 50° angle-of-attack.

Finally the rotating lift coefficient was maximised to the lift-coefficient for potential flow.

4.2 Corrigan & Schillings stall-delay

Corrigan & Schillings [5] developed a correction model for the effects of rotation, formulated as delay of separation to larger angles-of-attack. Here ‘separation’ is expressed as the ratio between lift coefficients for potential flow.

This derivation of this model is based on the pressure gradients in the boundary-layer, using equations similar as those by Banks & Gadd [1]. Together with the expression for the velocity gradient in the boundary layer \(\partial u/\partial z\) the amount of stall delay is related to the angular location of the separation point: \(\theta_s\), which implies a dependency on the chord/radius ratio similar as for other models.

A characteristic assumption behind this model is that airfoils with a high non-rotating maximum lift can have a strong suction peak at the leading edge which gives strong chordwise pressure gradients and correspondingly a stronger suction in the separated flow area. For simplicity the model of Corrigan & Schillings was finally formulated in the angular location of the trailing edge \(\theta_{\text{TE}}\). For not too large chord values this can be approximated with \((c/r)\).

The delay of stall is expressed with a shift in angle-of-attack for the non-rotating coefficients:

\[ \Delta \alpha = (\alpha_{\text{Cl,max}} - \alpha_{\text{Cl}} = 0) \cdot \left( \frac{\theta_{\text{TE}}}{0.136} \right)^n. \]

The value \(K\) describes the velocity gradient which fits to the universal relation: \(c/r = 0.1517/K^{1.084}\).

For \(n = 0\) this expression gives the non-rotating coefficients. Corrigan indicates that a value of \(n\) between 0.8 and 1.6 gives a good correlation with most data, and a value 1 gives good results for many cases. In the applications by Tangler & Selig [24] and by Xu & Sankar [26] \(n = 1\) was used.

The table with non-rotating coefficients is shifted over this stall delay angle \(\Delta \alpha\), where the lift coefficient is given an additional increase of:

\[ c_{\text{rot}}(\alpha + \Delta \alpha) = c_{\text{non-rot}}(\alpha) + \partial c_{\text{pot}}/\partial \alpha \cdot \Delta \alpha. \]

Here \((\partial c_{\text{pot}}/\partial \alpha)\) is the slope of the linear (‘potential’) part of the lift curve for which Xu & Sankar [26] used 0.1 for the phase-VI rotor.

4.3 Comparison of models

Figures 2 through 4 show the coefficients of the S809 airfoil of the UAE Phase-VI rotor as are obtained with the different correction models. For all coefficients the speed-ratio dependency was modelled with \((\cos \phi_{\text{inf}})^2\), where \(\phi_{\text{inf}}\) is the sum of the angle-of-attack, the local twist angle, and the 3.0° pitch angle used for most of the NASA-Ames wind tunnel measurements. For the correction of the S809

\[ \text{Figure 2: Rotating S809 coefficients at 30.0\%, } c/r = 0.4709, \ \theta_{\text{tw}} + \theta_p = 19.08^\circ \]

\[ \text{Figure 3: Rotating S809 coefficients at 46.6\%, } c/r = 0.2676, \ \theta_{\text{tw}} + \theta_p = 9.49^\circ \]

airfoil coefficients following the method of Corrigan & Schillings, the range \((\alpha_{\text{Cl,max}} - \alpha_{\text{Cl}} = 0)\) was determined at 16.4° for the 2nd maximum of \(c_l\) while the
5.1 Comparing sectional coefficients

The blade of the Phase-VI rotor has the S809 airfoil contour and was equipped with pressure taps in 5 sections. The data obtained from these pressure taps were processed by NREL to normal and tangential force distributions for each of the 5 sections.

The angle-of-attack distributions with the corresponding rotating lift and drag coefficients of the S809 airfoil were derived from these blade forces using the ECN program inflow, which has a vortex description of the rotor wake. No correction was applied for the 'blockage' effects from the tunnel walls. These measurements in the NASA-Ames wind tunnel were conducted for the wind speed values: 5.0m/s, 6.0m/s, 7.0m/s, 8.0m/s, ..., to 25.11m/s. The measurements used here were for a 3.0° pitch angle and a rotor speed near 72rpm (synchronous generator), without pitot tubes on the blades.

With the corresponding values for rotor-speed, air density, and wind velocity the aerodynamic coefficients were reconstructed with the vortex wake program inflow, see Appendix B of [16]. Because of the radial flow components near the blade root, and the strong influence of the 'suction area' in the rotor centre, the aerodynamic coefficients for the 30.0% section were not thought to be valid for comparison with models based on quasi-2D blades.

For the 5 instrumented sections the coefficients from both the non-rotating measurements (for 30m/s wind velocity), the rotating measurements, and the predicted coefficients are plotted in Figure 5 through 8. These figures also include the results from the EllipSys3D calculations by Risø, see [12, 23].

For the small wind speed values of 6m/s and 7m/s a relatively large area of the blade is not in stall. For those conditions the aerodynamic coefficients match well with the coefficients for the non-rotating measurements, the values for the smallest a.o.a., which gives confidence in the process applied with the tool inflow. Also the fact that the drag coefficients for small angles-of-attack are not negative shows that the tool inflow is not that bad.

The rotating coefficients in stall for the most inner section (30.0%) in Figure 5 show a (unrealistic) decrease in angle-of-attack for wind speed values increasing from 11m/s to 14m/s. This decrease in angle-of-attack, and the associated high lift coefficients may be caused by stall of the midspan region of the blade, which gives boundary-layer suction of the separation area of the root section. Although it is always wise to check for mistakes/deficiencies in the analysis tools (here inflow) it follows that the aerodynamics of a rotating blade can not be described easily on sectional basis. The decreas-

Figure 4: Rotating S809 coefficients at 63.3%, $c/r = 0.1701$, $\theta_{tw} + \theta_p = 5.89^\circ$
The angle-of-attack for the 30.0% section may be caused by interaction (sudden radial flow) between neighbouring sections. For the 30.0% section the EllipSys3D calculations did also show large values of the lift coefficient although they remain below the potential lift curve $2\pi (\alpha - \alpha_0)$.

For the 30.0% section Schreck and Robinson [19] found very large normal-force coefficients. The rotating coefficients for the 46.6% and the 63.3% section show an increased lift coefficient of the same amount as what is predicted with the ‘centrifugal pumping’ method. Contrary to this, the rotating lift coefficients for the 80.0% section show a small reduction in maximum lift, while the rotating lift coefficients for the 95.0% section appear to be much smaller than the non-rotating values. The smaller lift coefficients for the 95.0% section were also found by Sørensen with the Navier-Stokes code EllipSys3D [12, 23].

In general, it is felt that with the program ‘inflow’ the angle-of-attack for the 30.0% section (esp. in stall) is too small. Figure 7 shows that the lift coefficient at the 63.3% section drops (stall) at a 17° angle-of-attack which is for the 11m/s tunnel wind speed. At higher angle-of-attack or wind speed values the lift recovers to values up to 1.2, which was also found by Tangler [25]. An explanation may be the occurrence of local ‘stall cells’ which are hard to predict with BEM-based models.
the non-rotating values, except in deep stall. It can thus be concluded that for the UAE phase-VI rotor the effects of rotation include an increase of drag coefficients in stall for a large span of the blade.

5.2 Comparing rotor performance

A comparison of the measured rotor performance with that calculated with a design code such as PHATAS does not require analysis of the angles-of-attack. Although the overall rotor performance does not show the detailed blade load distribution, it is representative for the power production and for the design of the nacelle and the tower. The calculated performance in Figure 10 and 11 are obtained with the program PHATAS, which has a BEM model for the rotor aerodynamics.

![Figure 10: Measured and calculated shaft torque](image)

![Figure 11: Measured and calculated blade flap moment](image)

For wind speed values up to 8m/s the rotor is not in stall so that the measured and predicted shaft torque show a good agreement. This agreement is also due to the fact that the implementation of the Prandtl tip-loss factor in the BEM model of PHATAS was given serious attention with regard to the trailing-vortex distance short behind the rotor plane. For wind speed values from 10m/s to 15m/s the predictions with each of the correction models give a higher torque than measured. For 10m/s and 11m/s the predictions with the 2D aerodynamic coefficients are even larger that the measurements from which it is concluded that comparing calculations with measurements for simple conditions is already hard, and that fitting of correction models to measurements does not necessarily lead to improvements. By the relatively good agreement of the EllipSys3D results and the BEM-based predictions with the different correction models one may rise some doubts about the accuracy of the measurements.

Although it was known in advance that no model was made for the 'end effects' near the root and the tip (which have a large influence for the low aspect-ratio Phase-VI blade) it is surprising to see that the calculations with the 'Centrifugal pumping' model gives a relatively good agreement with the measured root flapping moment at the high wind speeds.

6 Concluding Remarks

General

The model of Snel et al. fits reasonable

Although the quadratic fit \((c/r)^2\) differs from the relation for ‘centrifugal pumping’, it matches well with the excessive rotational effects at the root.

Rotor-average effects fit quite well

Although (stable) local stall cells may occur, the rotor-average effects of rotating aerodynamic coefficients can be calculated with reasonable accuracy using existing empirical models.

Centrifugal pumping model

Dependency on speed ratio

In several models it was assumed that the rotational speed of the sections dominates the wind velocity. For use in wind turbine design codes the start, stop, and idling conditions require a smooth transition from non-rotating to rotating coefficients, which is included in the Centrifugal pumping model. This 'local speed-ratio' dependency reduces the rotational effects to very small values when approaching a 90° a.o.a., while other models need an empirical 'decay' to the 2D coefficients.

Rotating drag coefficient

Many measurements also show an increased drag, which fits to the fact that ‘centrifugal pumping’ of air requires energy. Knowing that for trailing-edge stall the additional suction the radial flow gives an increased normal force coefficient, and also including an 'angle-of-attack' delay, results in a
model for drag. Unfortunately it is hard to obtain accurate drag measurements.

Difficulties / remaining questions

Tip and Root effects As for many stall delay models, the model derived here is based on (stalled) flow that is continuous over the span. As is shown here this gives deviations for the tip region and the root region. These ‘end-effects’ require detailed modelling. At the ‘root-end’ one has to deal with a complex aerodynamic flow of which the root vortex is badly defined. For the ‘tip-end’ an empirical model has been developed and implemented in PHATAS and BLADMODE, see section 4.6 of [16].

Assess basis for rotating coefficients

Measurements on rotating rotor blades showed high peak values near the leading edge. For realistic application of correction models for rotational effects one first has to assess coefficients with the formation of leading-edge stall and separation bubbles suppressed.

Airfoil dependency Knowing that ‘stall delay’ is related to the location of the separation point, the ‘amount’ of angle-of-attack delay may show a strong dependency on the airfoil shape, most likely for thick airfoils. The result is that most correction models have one or more parameters or a scaling factor.

Stall is not uniform over the blade span

Investigations of measurements on the UAE Phase-IV rotor showed that local stall may appear, and be stable. Although this is not always the case most models do not account for local stall.

The measurements on the UAE Phase-VI rotor used in the comparison reported here were for a 3° pitch angle. It is suggested to also use the measurements for the 6° pitch angle because they go less deep in stall, and because this allows separate evaluation of the dependency on angle-of-attack and the ‘local speed-ratio’. Another set of measurements was conducted with extended tips, which is interesting because this allows investigation of the end-effects on the 63.3% and 80.0% sections.

References


[24] Tangler, J.L. (NREL) and Selig, Michael S. (Univ of Illinois, Urbana); 'An evaluation of an empirical model for stall delay due to rotation for HAWTs'. In Proceedings Windpower '97, Austin TX, pp.87-96.

[25] Tangler, J.L. (NREL); 'Insight into a Wind Turbine Stall and Post-Stall Aerodynamics'. In Proceedings Windpower '03, Austin TX.
