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REVIEW of RECENT AERODYNAMIC RESEARCH on WIND TURBINES with relevance to ROTORCRAFT

Data (and riddles) on DYNAMIC INFLOW, FLOW FIELD OF YAWED ROTORS, and ROTATING 3-D STALL

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REVIEW of RECENT AERODYNAMIC RESEARCH on WIND TURBINES with relevance to ROTORCRAFT

Data (and riddles) on DYNAMIC INFLOW, FLOW FIELD OF YAWED ROTORS, and ROTATING 3-D STALL

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1. SUMMARY
A review is given of recent research on the aerodynamics of wind turbine rotors. The following subjects are covered in extenso:

- The induced velocity field of rotors, including dynamic inflow and yawed flow effects.

- Stall delay on rotating blades. A new boundary layer formulation is outlined applicable to this phenomenon.

Without any further discussion, also some references have been given concerning recent wind turbine research on:

- simulation methods of atmospheric turbulence,
- dynamic stall effects, comparisons between theory and experiments,
- Effect of several types of blade tips on radiated noise.

2. NOTATIONS

a	induction factor v_i / U
$C_{D,ax}$	drag coefficient of entire rotor
C_y	axial force coefficient of blade section
R	rotor radius
r	local radius
t	time
U	free stream velocity
V	total resulting velocity at blade section
v_i	induced velocity in disc plane
σ	solidity
τ	time constant, or shear stress

other notations explained in figures

3. INTRODUCTION
This paper presents a review of recent aerodynamic research related to wind turbine rotors, which may not be very well known outside the "wind community" but may nevertheless have relevance for rotorcraft as well.

The requirements for a long, maintenance-free life and low first cost of wind turbines have stimulated the development of accurate prediction methods of extreme aerodynamic loads and fatigue spectra. Furthermore, a considerable amount of research has been done in order to reduce aerodynamic loads by proper control systems and by flexible rotor systems which employ the same principles as hingeless helicopters.

Apart from the obvious similarities between the rotors and aerodynamics of wind turbines and rotorcraft, there are also typical differences. The disc loading of wind turbines is high, so that normal operation is often close to the turbulent wake state, with values of the induction factor a = v_i/U around 1/3. This implies close proximity of the free vortex sheets to the disc, and large self-induced deformations of the wake configuration. Linearization applied in helicopter aerodynamics must often be questioned for wind turbine applications. In the case of a hovering rotor the loading is also high in an aerodynamic sense (i.e. there is a large influence of self-induction on the wake configuration). In the case of the helicopter this results in a contracting wake, whereas the high loading on a wind turbine rotor results in wake expansion.

A high blade loading of turbine rotors is another typical feature. In fact, stalling is often used as a means of limiting the power absorbed from the flow. Stalled flow is thus effectively part of the operational envelope of the turbine.

Finally, the rotor dimensions of a turbine are generally larger than those of rotorcraft. The scale of the turbulence experienced by wind turbines, operating close to the ground, is for that reason more comparable to the radius. A strong "rotational sampling effect" (in rotorcraft literature sometimes referred to as "rotating frame turbulence") is therefore always present.

During the "pioneering phase" of modern wind turbines - roughly from 1970 until 1980 - much aerodynamic knowledge was borrowed from aeronautics, in particular from the field of helicopters. In a later phase, dedicated R&D programs have emerged, directed at the specific aerodynamic problems of wind turbines where the need was felt to improve upon the available rotorcraft knowledge.

For the "helicopter community" the results of this work may be interesting, since well known theoretical models have in this way have been verified in flow regions outside the usual range of parameters. Some unexpected discrepancies between models and experiments have indeed shown up.

4. SOME REFERENCES TO RELEVANT RESEARCH WICH IS NOT FURTHER DETAILED IN THE PAPER
Apart from the projects discussed in the paper in some detail, other relatively large scale research projects on windturbines have recently been completed. For lack of space they could not be included in the present review. It may nevertheless be useful to give here some relevant references, without pretending to be exhaustive. These research subjects were:

- Modeling of inflow turbulence, as "felt" by rotating blades: ref.1, based on the earlier work of ref.2.

- Experiments on dynamic stall and comparisons with theory: ref.3.

- Noise research, in particular the influence of several types of tip shape: refs.4 and 5.

5. DYNAMIC INFLOW EFFECTS IN AXIAL FLOW

5.1. Background of CEC-research on dynamic inflow

Research on dynamic inflow effects of wind turbines was initiated after it had been observed that sometimes large, unpredicted blade loads occur during fast braking of wind turbines by blade feathering. The phenomenon was qualitatively explained as a "dynamic inflow" effect.

Apart from the effect of dynamic inflow, blade forces during transient operating conditions may also be influenced by unsteady profile characteristics. However, the typical time scales of dynamic inflow effects and of unsteady section aerodynamics are well separated. The possible influence of unsteady profile aerodynamics may be estimated, e.g. using the ONERA-model (ref.6). From such exercises it can be concluded that during typical pitching steps of wind turbines the unsteady profile characteristics play a minor role.

There is a long history of inflow modeling in helicopter aerodynamics, see Chen (ref.7). One of the most successful methods for the estimation of dynamic inflow effects for helicopters is based on the work of Pitt and Peters (with a large and ever growing number of associates, see i.a. ref.8, based on the earlier ref.9).

However, in view of the above mentioned differences between the helicopter rotor and the highly loaded turbinerotor, research was initiated by the CEC, within the Joule-program, on dynamic inflow effects in the case of wind turbine rotors. The aim of this research program was to generate an experimental database of typical dynamical inflow effects as encountered by highly loaded turbinerotors, and compare this with the predictions obtained by several theoretical methods.

5.2. Brief description of experiments and theoretical models

1) Experiments.
Although several wind turbines and windtunnel models were used, the most important experiments were performed on the Tjaereborg 2 MW turbine (60 meters diameter) in Denmark.

Data were measured under the following conditions:

- fast pitching steps
- emergency stops by feathering
- yawed operation

The most interesting results were found for the case of small pitching steps. For this reason we will concentrate on this case in the following. Complete results of the project will be published in the final report on the project, not yet available.

2) Theoretical methods.
The theoretical methods covered a wide range of different approaches:

I. Free-wake models. Three different models were investigated, based on either vortex lattices, vortex particles or on a description in terms of the acceleration potential.

II. Comparisons were made with a simple prescribed-wake model, where the wake was modeled as a vortex tube with varying vortex strength.

III. Several engineering models were investigated as well. These were based on blade element - momentum theory, modified by formulating them as first-order differential equations to simulate the time lag. Three different models were investigated, where the time constants were derived from three different theoretical analyses.

Before results of the comparisons are shown, a brief decription of these models will be given.

<u>Free-wake, lifting surface model using vortex particles</u> (National Technical University of Athens)

The computercode GENUVP of NTUA is a time-marching code based on a consistent combination of the boundary element method and the vortex particle method. The boundary elements consist of distributed dipoles on the solid surfaces of the flow. The boundary conditions of non-penetration determine the intensities of these distributions. The vortex particles are used to simulate the generation and evolution of the free vorticity. The vorticity shed along the edges of the blades is locally integrated and assigned to point vortices (or equivalently, to fluid particles carrying vorticity). Next the evolution of these vortex particles is followed by integrating the vorticity transport equations in Lagrangian coordinates. For further details, see ref.10.

<u>Free-wake, lifting surface model using vortex filaments</u> (University of Stuttgart, IAG)

In this free wake code (ROVLM) the blade is covered with panels on which a constant dipole strength is assumed. The induced velocities are calculated with the Biot and Savart law using the vortex strength corresponding to the differences of the dipole strengths on adjacent panels. Due to the external flow field and the induced velocities at the blade, points from the separation edges move downstream and build up the panels of the free wake which are deformed in such a way that the forces on the wake vanish. The kinematic boundary condition on the blade is fulfilled in the model. For further details, see ref.11.

Free-wake, lifting line model using the acceleration potential (Delft University of Technology, Inst. Wind Energy)

This code (PREDICHAT)is based on an unsteady lifting line theory which was originally developed for helicopter rotors (ref.12). In order to modify classical lifting line theory in such a way that it becomes usable and consistent under unsteady and yawed flow conditions, a rigorous matched asymptotic expansion method was applied to derive lifting line theory from first principles. This was facilitated by using the acceleration potential for a description of the flow field. When this theory is applied to rotors, analytical expressions are derived for the complete, time varying pressure field associated with the rotorblades. As a next step the corresponding velocity field is found by numerically integrating the acceleration of fluid particles coming from far upstream and finally reaching the near field of the rotor. Although the Laplace equation for the pressure field is derived by linearizing the flow equations, in the present code PREDICHAT the most important non-linear effects are taken into account. This is achieved by letting the path followed by the particles completely free, which simulates the free-wake effects. The method is computationally very efficient, because use is made of closed form solutions for the pressure field. It is a free-wake method which may be run conveniently on a normal PC. For further details, see ref.13.

Simple prescribed wake model (Energy Research Foundation Netherlands ECN)

The induced velocities in both axial and tangential direction are calculated with a cylindrical vortex sheet model. The vortex distribution on the cylindrical wake is obtained by the time history of the shed tip-vorticity which is related to the axial force on the blade. With the Biot-Savart law the induced velocities can then be found. It is assumed that the wake extends up to four rotor diameters downstream. Inputs that may be semi-empirically adjusted are the axial convection velocity and the effective diameter of the cylindrical wake. For further details see ref.14.

Differential equation model, with time contant based on the simple prescribed wake method (Energy Research Foundation Netherlands ECN)

The induced velocity in axial direction within an annulus of the rotor disc is calculated with the blade element- momentum equation with the addition of a time derivative of the induced velocity:

$$4\ R\ f(r/R)\ \frac{dv_i}{dt} = C_{D,ax}\ U^2 - 4\ v_i\ (U - v_i)$$

The value of the time constant f(r/R) is deduced from the equations for the cylindrical wake mentioned above (ECN, simple prescribed wake model):

$$f(r/R) = 2\pi / \int_0^{2\pi} \frac{[1 - (r/R)\cos\phi]\ d\phi}{[1 + (r/R)^2 - 2(r/R)\cos\phi]^{3/2}}$$

The function f(r/R) equals 1 for r/R=0 (the rotor centre) and 0 for r/R=1, the rotor edge. Hence the time constant for the rotor centre position equals 4R/U, while at the rotor edge the time constant equals zero, so that the equilibrium relations always hold there. This can be seen to be a natural consequence of the cylindrical vortex wake model. In fact, the only vorticity inducing axial velocity at the tip is the vortex in the process of being released, while at the rotor centre a large portion of the wake, and hence of the time history, causes axial induced velocity.

For large induced velocities, particularly for v_i/U >.5, the blade element momentum theory is not valid, the turbine operates in the socalled turbulent wake state. In the actual implementation a model for the latter effect is used for a > .38, where the right hand side of the above differential equation is replaced by:

$$\text{r.h.s.} = C_{D,ax}\ U - 0.96\ v_i + 0.5776\ U$$

Differential equation model based on Pitt & Peters time constants (Garrad, Hassan & Partners, UK)

This model is based on the same ideas as the previous model.
The time constant, however, is taken from the method of Pitt and Peters (ref.8). The original method is on an global disc level. For a disc of radius R the apparent mass is given approximately by potential theory (Tuckerman, ref.15) as 8/3 ρR^3, but is in the present method applied on blade element level. This results in a differential equation for the axial induction factor a:

$$\frac{16\ (r_2^3 - r_1^3)}{3\pi U\ (r_2^2 - r_1^2)}\frac{da}{dt} = \frac{\sigma\ V^2}{U^2} C_y - 4a(1-a)$$

In contrast to the earlier described differential equation model by ECN, in this case the time constant grows linearly with r (together with the area of the respective annuli).

Differential equation model with two different time constants (Technical University of Denmark)

The induced velocities in axial direction are calculated with the blade element-momentum equations with the addition of a time derivative of the induced velocity. This is similar to the models given above. TUDk however uses two differential equations. These have the following form:

$y + \tau_1\ dy/dt = x + k.\ \tau_1\ dx/dt$

$z + \tau_2\ dz/dt = y$

with k = 0.6 and:

$$\tau_1 = \frac{1.1}{(1 - 1.3\ a)} \frac{R}{U}$$

$\tau_2 = (0.39 - 0.26\ (r/R)^2)\ .\tau_1$

This amounts to one short and one longer time scale for the decay. The time constants weakly depend on the radius of the blade element. The time constants are derived from an actuator disc - vortex ring program which includes the effect of wake expansion.

5.3. Results

Typical results of the comparisons between the experiments and the theoretical models are shown in the figures 1 and 2.

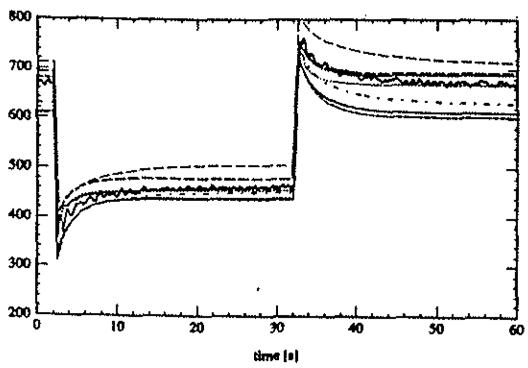

Fig.1: Measured and predicted flapping moments at blade root. Measured data: irregular full line.

What is shown here is the effect of pitching steps on several forces and moments measured on the Tjaereborg windturbine. During these transients, after an initial period the blade pitch angle is first increased at a fast rate of approx. 3.5°/s, next maintained constant for about 30 seconds and then decreased to its initial value at the same fast rate. The measurement period extends over a total of 60 seconds. Measured values for blade and shaft loads have been averaged over a number of realizations, and over the three blades in order to filter out stochastic wind influences and deterministic effects such as (average) windshear and tower shadow.

For the case discussed here the average windspeed was 8.7 m/s. The value of the calculated equilibrium induction factor a = v_i/U may serve as an indication of the loading situation. This factor was a = 0.34 before the pitching steps were applied, whereas a = 0.23 was calculated after the first transient.

Fig.1 shows the flapping moments at the blade root. The irregular full line shows the measured values. It must be realized that the response shown by the experimental line includes flapping motions due to flexibility of the blades. The bundle of other lines gives an impression of the levels found from the computational results.
Similar results are shown in fig.2 for the rotorshaft torque.

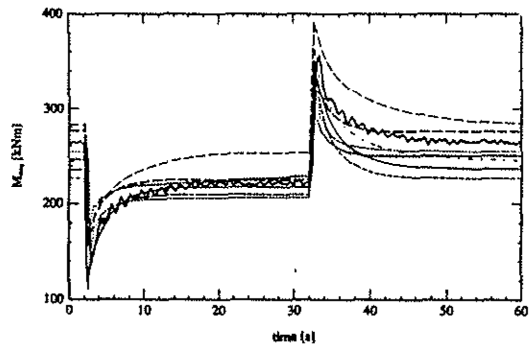

Fig.2. Measured and predicted rotorshaft torque. Measured data: irregular full line.

Both the measured and the calculated curves show that there is indeed a large overshoot of the forces and moments due to the dynamic inflow effect. The overshoot damps out in approximately 10 seconds which, as would be expected, corresponds very roughly to convection of the wake vorticity over a distance of between 1 and 2 diameters.

Closer examination of these and other results reveals the following:

- the equilibrium ranges (i.e. the difference between the equilibrium values) predicted with the differential equation models are consistently lower than those of the measurements, while those of the wake models compare very well with the measurements.

- In contrast to this, it appears that the dynamic ranges calculated by the engineering models (the differential equation models) are in good agreement with the measured values, whereas the dynamic ranges calculated with the free wake models are consistently lower.

- The differential equation models differed mainly in the value of the time constants chosen, and the variation of the time constants with radius. These differences do not really show up in the comparisons with the measured blade loads.

5.4. Discussion

5.4.1. One of the striking results is, that the differential equation methods show a relatively poor performance as far as the equilibrium predictions are concerned. This problem has no relation with the way in which the dynamic effects have been modeled. In fact, the straight-forward application of very classical blade element-momentum theory appears to be the weak point !

This observation is found in the literature more often (e.g. Viterna and Corrigan, ref.16). At present it is sometimes suspected that such problems might be of a rather more fundamental nature than just the incorrect "tuning" of for instance a tip-correction factor.

For instance, Van Kuik (ref.17) doubts the internal consistency of any disc-type model of the flow, when no attention is paid to the edges of the disc, where singularities might occur (similar to the "nose suction" of aerofoils or "edge suction" on wingtips).

Apart from this there may be other inconsistencies, inherent in the way these inflow models are coupled to blade-element theory. The momentum models as well as Pitt and Peters's theory try to predict the socalled "induced velocities" which, in combination with a blade-element consideration, will yield the forces on the blade. "Induced velocity" as used in this sense is a typical lifting-line concept. It is not a measurable physical quantity, but rather a theoretical concept, originating from Prandtl's classical lifting concepts for the straight wing in steady flow.

It is well known that lifting line theory as classically formulated breaks down in the case of swept wings and in unsteady flow, among other reasons due to singularities occurring along the lifting line if analyzed correctly. In rotating flow, where the streamlines relative to the blade are curved, no singularities occur, but nevertheless lifting line theory is neither strictly valid.

By Van Holten (ref.12, 18) the lifting line theory for swept wings and for unsteady flow was investigated in a more rigorous way, using a matched asymptotic expansion technique. It was found that in classical lifting line theory a term is neglected which is not important for the straight wing in steady flow, but which is essential in more complicated situations.

From the asymptotic theory it appears that the complete flow field in lifting line theory (the "composite field") should be considered as a sum of three contributions:

1) The "far field", corresponding to the contribution of the free trailing and shed vorticity in the wake.

2) The "near field", corresponding to the velocity field of a two-dimensional unsteady profile, including its wake of shed vorticity,

3) The "common field", to be subtracted from the far field, which cancels the singularities in unsteady flow, and at the same time prevents a double count of the shed vorticity near the wing.

The situation is schematically depicted in fig.3 for the unsteady case. "Induced velocity" in Prandtl's sense is the difference between 1) and 3).

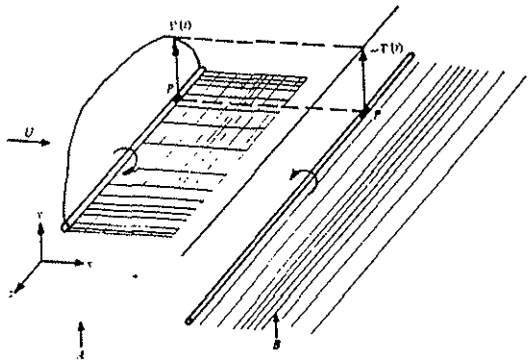

Fig.3: Definition of induced velocity at P; sum of contributions of vortex systems A and B.

In the case of a swept wing analogous effects, mathematically resembling the above unsteady effects, occur. Although not analyzed in ref.12 and 18, from the theory it is clear that a wing relative to which the streamlines are curved must in principle experience similar phenomena, making the classical lifting line concepts less valid.

From this brief summary it will be clear that in unsteady, yawed or circular flows the concept of "induced velocity" is more of a theoretical notion - though mathematically well defined - than a physical quantity that can be measured at some place in the field.

At present it is thought that the above considerations deserve more attention and caution when inflow models of rotors are used such as Pitt and Peters' or vortex-tube models and conceptually comparable ones. What is to be determined by such models (if the calculated velocity is consequently used in a blade-element method) is the "induced velocity" in the lifting line sense, and not a real, physical velocity.

Other models used during the above described dynamic inflow calculations do not suffer from these conceptual difficulties. The free-wake models using flow field descriptions in terms of either vortex lattices or vortex particles (refs.10 and 11) are both essentially based on lifting surface theory, where concepts like "induced velocity" (in Prandtl's sense) and "two-dimensional section characteristics" do not play a role, and do not even have a meaningful definition. The third free wake method (ref.13) using the acceleration potential for the field description is based on an unsteady lifting line theory where all the three earlier mentioned field components are correctly taken into account.

5.4.2. Also disappointing is the relatively poor performance of the elaborate free-wake methods, as far as the dynamic effects are concerned. This has led to an in-depth discussion about questions of stability, convergence and accuracy of these methods.

The free vortex wake models are based on an exact formulation of the inviscid flow equations. However, the numerical discretization procedure into either vortex lattices or vortex particles warrants special attention. An exception to this is the free-wake lifting line method based on acceleration potential theory, where no discretizations of this type are necessary.

Such a discretization artificially introduces singularities in the description of the flowfield. Nevertheless, in a case where the position of the singularities is fixed in space (linearized theory) or is prescribed beforehand as a function of time on the basis of experiments ("prescribed wake methods"), it can be shown that the correct inviscid limit is approached when the number of discrete vortex elements is increased indefinitely.

In the case of freely convecting vortex elements ("free wake") there may occur a computational stability problem due to the very irregular flow field associated with the discretized singularities. For this reason artificial desingularization (or: "regularization") is used in both the free-wake vortex methods by the introduction of a "cut-off" length: close to the singular points a regular flow field is substituted in place of the almost singular flow field near the discrete singularities. In principle there is no guarantee that the convergence characteristics are still maintained under these circumstances.

A simple test case has been used to obtain some insight in this question. The test case consisted of a two-dimensional strip on which vorticity is continuously distributed in such a way that the self-induction is constant along the strip. Although the test case is mathematically very simple and possesses an exact solution in closed form, in some respects it is very demanding for the numerical solution methods. What is in fact tested is, how accurately a numerical calculation will predict the free convection of vorticity in the edge region of the vortex sheets.

It was concluded that a free wake analysis will be stable as well as convergent if care is taken that, when the grid size and time steps are decreased, at the same time the cut-off lengths are reduced such that a specific ratio between all these quantities is maintained.

The finally remaining question is then, how accurate the numerical free wake analyses are in the case of a practical choice of grid size and time step. This proves to be the weak point. The problem is not of a fundamental nature, but is associated with the speed and capacity of the presently available computers. In conclusion it can be said that in those flow regions where the deformations of the free vortex sheets are large the grid size would probably have to made much smaller than is practically feasible at present.

6. VELOCITIES AND FORCES IN YAWED FLOW

6.1. Theoretical models and experiments

For wind turbines yawed operation may strongly affect load spectra of the blades and shaft. The same Joule-program as described above on dynamic inflow also covered an investigation of load prediction methods associated with yawed flow situations.

Again measurements were performed using the Tjaereborg windturbine (60 meter, 2 MW). Additional measurements were performed on windtunnel models, at Delft University of Technology, Institute for Windenergy.

The more elaborate free-wake vortex models were the same as used during the "dynamic inflow" research. These free-wake models do not require any essential changes in order to analyse yawed flow.

Simpler engineering models were essentially implementations of the "Pitt and Peters" method (ref.8). The Pitt & Peters model is a description in terms of first and higher harmonics of the relation between dynamic disc loads and inflow, based on an expansion solution of the (yawed) flow across an actuator disc.

6.2. Results

A comparison between measurements and the prediction by "Pitt and Peter" type models is shown in fig.4. The figure shows the contribution of the blade bending moments to the restoring yaw moment of the Tjaereborg turbine at 32° and -51° yaw angle respectively. The comparison shows fair agreement, but certainly not very good. Although not shown in the same figure, the results of the free wake calculations show the same general behaviour.

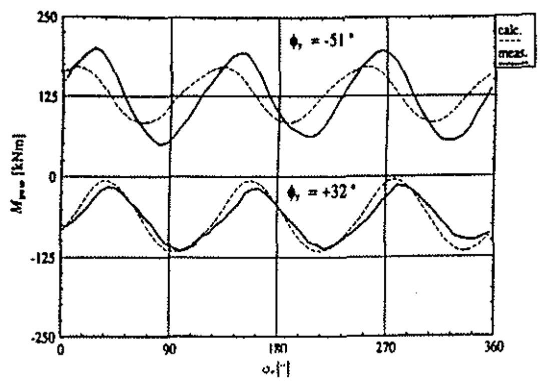

Fig.4: Contribution of blade bending moments to restoring yaw moment at 32° and -51° yaw angle. Comparison of measurements and calculations. Definition azimuth angle: see fig.5.

Windtunnel experiments (ref.19) made it possible to do measurements of the inflow itself, at different positions directly behind the rotor plane. Information at this level is very important to improve the modeling. Some data of the tunnel, the model and the measurement setup are shown in fig.5.

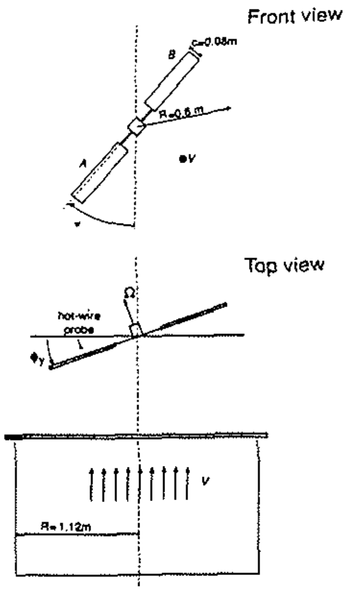

Fig.5: Windtunnel setup and notations.

Fig.6 shows the measured axial velocity at a number of radial stations, as functions of the azimuth, for a yaw angle of 30°. The measurements have been averaged over one revolution of the rotor. Apart from the tip sections (90% and 95% radial position) the induced velocity appears to have a <u>maximum in the "upstream" region of the disc, contrary to theoretical predictions !</u>

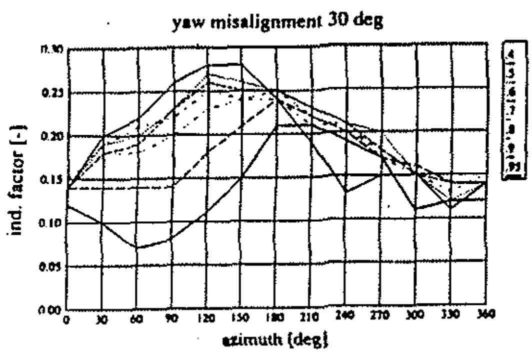

Fig.6: Measured axial induction distribution, wind tunnel.

6.3. Discussion of the discrepancies between theoretical and experimental results.

A number of intriguing questions thus remain for further research.
Several hypotheses have been put forward to explain the qualitative disagreement between the windtunnel measurements and calculations of the field of inflow, so far in vain however. Nevertheless, the search for an explanation has been very fruitful, because it was instrumental to uncover several effects that appear to have been overlooked often in the literature on rotor flow calculations.

1) The hot wires used for the flow measurements were placed in a vertical position, so that the resulting velocity in a horizontal plane was measured.
Simple skewed vortex tube models show that <u>in-plane induction velocities</u> will occur, apart from the perpendicular induction velocity which is being sought primarily. These additional in-plane velocities are often neglected in blade-element analyses, although they will definitely influence the advancing-retreating blade effect.
An order of magnitude estimate showed however, that the influence of the in-plane induction on the hot-wire measurements cannot explain the noted discrepancy between windtunnel and prediction.

2) The situation of a wind turbine rotor is, as already stated in the introduction, somewhat different from a helicopter rotor. In the case of the mentioned windtunnel tests, there was no flapping motion of the blades so that the "rolling" and "pitching" moments of the rotor were much larger than usual for a rotor with flapping freedom. Also, the shed vorticity associated with the advancing-retreating blade effects will be much stronger. Especially the latter phenomenon is not considered in the Pitt/Peters model. At present a further investigation of these effects by comparison with detailed free-wake calculations is being done.

7. THREE-DIMENSIONAL SECTION CHARACTERISTICS, AS INFLUENCED BY BLADE ROTATION

7.1. Background of research into stall characteristics

It is well known that the influence of rotation on the profile characteristics of rotorblades may be appreciable, especially near stall. In particular the inboard parts of a rotating blade may show a much larger $C_{l,max}$ than would be expected on the basis of two-dimensional section characteristics.
In the case of wind turbines the phenomenon is very important for the prediction of performance and loads, because blade loadings are generally high. Operational conditions often occur where the inboard part of the blades is on the verge of stalling or is indeed stalled, for instance when stall-regulated rotors are employed.

It was recently pointed out by Corrigan (ref.20) that stall delay due to rotation is also important for the performance and load prediction of highly loaded lifting rotors such as used in tiltrotors and highly maneuverable helicopters.

A theoretical and experimental investigation of the phenomenon was done in the Netherlands, by ECN, NLR and TUD under a contract by NOVEM.

7.2. A boundary layer theory for rotating blades

The essential core of the research was a new formulation by Snel (ref.21) of the boundary layer equations on a high aspect ratio rotating surface similar to a rotorblade (for notations, see fig.7). An order of magnitude analysis of the terms occurring in the boundary layer equations leads to the conclusion that in attached flow the usual two-dimensional boundary layer equations are recovered, exact up to terms of the order $O(c/r)$:

$$\frac{\partial u}{\partial s} + \frac{\partial w}{\partial z} = 0 + O(c/r)^2$$

(continuity equ.)

$$u\frac{\partial u}{\partial s} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial s} + \frac{1}{\rho}\frac{\partial \tau_1}{\partial z} + O(c/r)^2$$

(chordwise momentum)

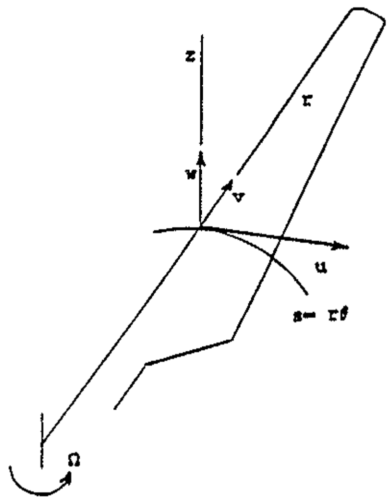

Fig.7: Rotating boundary layer analysis, notations.

If desired, one can also set up a spanwise momentum equation for the velocity component v in radial direction. One can see from the equations above however that to first order the chordwise flow is not coupled with the radial flow component v, and the situation is essentially two-dimensional.

Furthermore, it appears that all the terms in the spanwise momentum equation are of order $O(c/r)$ or smaller compared with the chordwise momentum equation. Hence, the boundary layer effects associated with the radial flow are weak.

In the case of separated flow, the situation is different, however. Now the fluid is essentially transported with the blade. Physically one may reason that the chordwise pressure gradient is small compared to its value in attached flow. Under these assumptions an order of magnitude consideration leads to the conclusion that, neglecting terms of $O(c/r)^{2/3}$, the relevant boundary layer equations become as follows:

$$\frac{\partial u}{\partial s} + \frac{\partial w}{\partial z} = 0 \quad \text{(continuity equ.)}$$

$$u\frac{\partial u}{\partial s} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial s} + \frac{1}{\rho}\frac{\partial \tau_1}{\partial z} + 2\,\Omega\,v$$

(chordwise momentum)

$$u\frac{\partial v}{\partial s} + w\frac{\partial v}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{1}{\rho}\frac{\partial \tau_2}{\partial z} + \frac{(u - \Omega r)^2}{r}$$

(spanwise momentum)

We see that in the chordwise momentum equation a Coriolis force has appeared, which couples this equation with the radial flow. Furthermore, it appears that the radial flow terms are no longer smaller in magnitude than the terms in the chordwise momentum equation, and may therefore no longer be neglected. The radial flow is clearly driven by centrifugal forces in the case that $u \ll \Omega r$, and by the radial pressure gradient.

In the equations as they are shown, a few terms have been kept which are of a smaller order than in fact would be relevant in the present order of approximation. Strictly speaking, in separated flow the centrifugal term in the spanwise equation might be approximated by $\Omega^2 r^2$. The advantage of the above given formulation is, that is covers both attached flow as well as separated flow, and gives a smooth transition in between.

Looking at the resulting expressions, the physical explanation of the differences between 2D stall and 3D separation on rotating blades can now be understood as follows. Significant radial flow can only develop in regions of strongly retarded flow (with respect to the blade) such as separation regions. Flow towards the tip develops at the suction side of the blade and results in a Coriolis force in the main flow direction, which acts as a favourable pressure gradient. This decreases the displacement thickness of the separated boundary layer, leading to less decambering and higher lift coefficients.

Apart from the physical insight provided by the above given equations, there is also a mathematical advantage in this formulation. In all the equations the advection operator (i.e. the non-linear left hand sides of the momentum equations) remains two-dimensional. The system of equations can be simultaneously solved in a way which is similar to the usual two-dimensional boundary layer calculations, along chordwise strips. In the boundary layer equations, the chordwise momentum equation is coupled with the spanwise equation through the Coriolis acceleration. In the computational procedure, this coupling term can be handled in a way analogous to the term expressing the chordwise pressure gradient.

The above boundary layer equations were implemented in a 2D viscous-inviscid strong interaction code, meaning that the chordwise pressure gradient is derived from the inviscid outer flow, while taking into account that the outer flow is strongly influenced by the development of the boundary layer. The code in question was the ULTRAN-V code, developed at NLR for the prediction of unsteady viscous transonic flow about oscillating aerofoils (refs.22 and 23).

7.3. Experimental verification and results
Computational results were compared with experimental data, derived from ref.24. A few results are depicted in fig.8 and 9.

computations were performed for an 18 % thickness section, at an assumed Reynolds number of $Re = 0.5 * 10^6$ and natural transition with a downstream limit of 50 % chord.

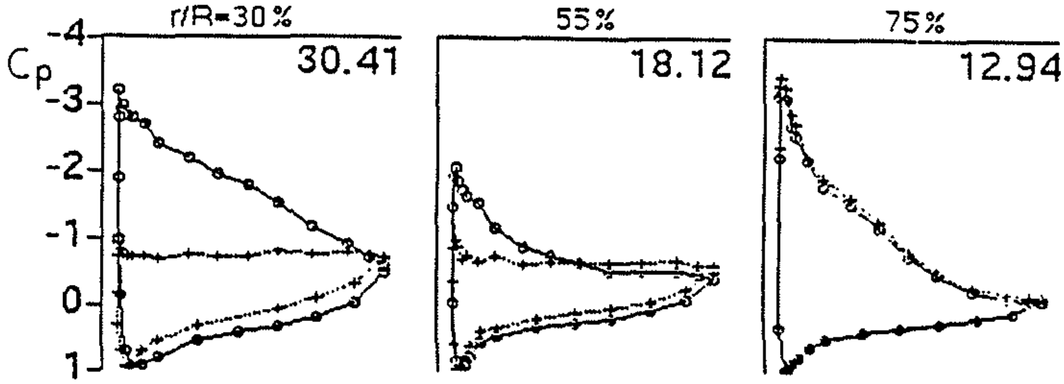

Fig.8: Experimental pressure distributions for the rotating blade (circle) and the non-rotating blade (cross).

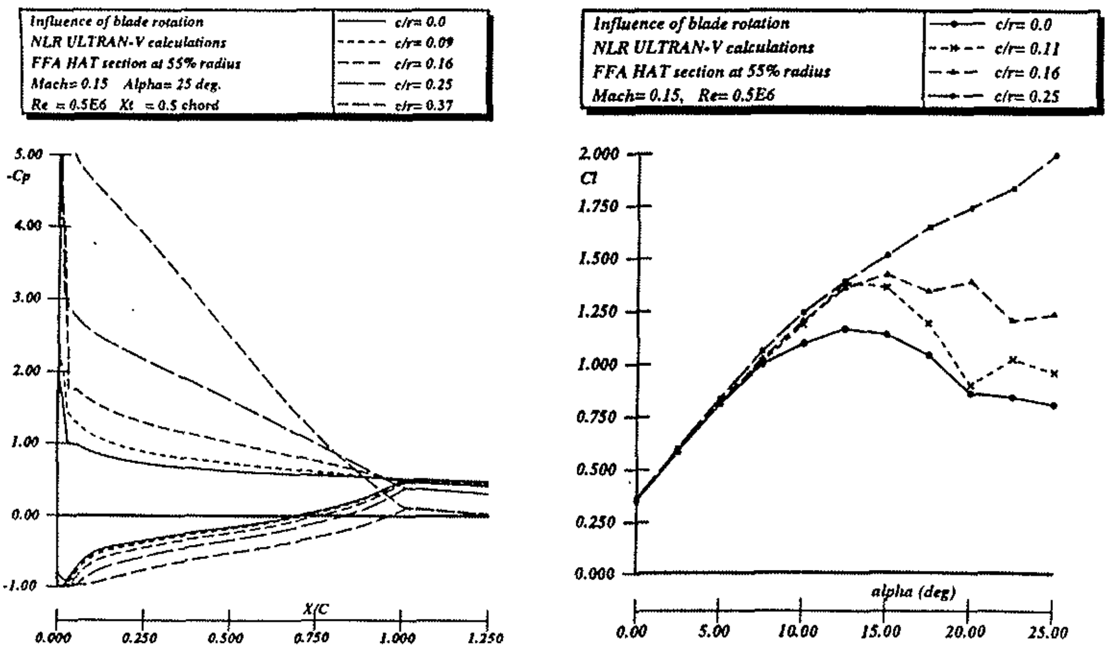

Fig.9: Calculated pressure distributions for rotating blade, geometry of fig.8.

Fig.8 shows measured pressure distributions at several radii of a wind turbine blade, for the rotating as well as the non-rotating case. The measurements were performed in the 12 * 16 m windtunnel of the China Aerodynamic Research and Development Centre (CARDC), using a blade of approx. 2 m length (ref.24). Especially at small values of c/r it is very clear that separation may be suppressed almost completely by the 3-D rotational effects. Calculated results of the effect of rotation are shown in fig.9. The

It appears that the agreement is qualitatively good. Quantitatively however, there is a discrepancy, because in the computation a smaller value of c/r had to be taken in order to reproduce the measured pressure distributions.

In future it is, among other possible refinements, intended to better represent the three-dimensional environment. For the determination of the radial pressure gradient, it was until now assumed that the spanwise pressure gradient is proportional to $\Omega^2 r^2$. This assumption is certainly unjustified near the root and near the tip, where rapid changes in the bound circulation will occur.

Another possible improvement will be, to make a formal asymptotic expansion of the boundary layer equations in terms of c/r, and include the next higher order terms.

For the time being, the results of the investigations were synthesized into a simple engineering formula. For this purpose several calculations were made with the ULTRAN-V code for a test rotor built and tested by the Delft University of Techology equipped with a NLF(1)-0416 aerofoil, as described in ref.25. The computations were made for a Reynolds number of one million at a "corrected" spanwise position to account for the earlier mentioned discrepancies between test and theory. In the resulting formula, similar to engineering formulae for unsteady aerodynamics or dynamic stall, a correction is expressed in terms of the difference between the 2D measured liftcoefficient and the inviscid lift coefficient, by multiplying this difference with a factor and adding to the 2D value:

$$c_{l,3D} = c_{l,2D} + f.(c_{l,inv} - c_{l,2D})$$

The multiplication factor f is for the time being only a function of c/r:

$$f = \tanh(3 .(c/r)^2)$$

Typical results obtained by this engineering formula are shown in fig.10.

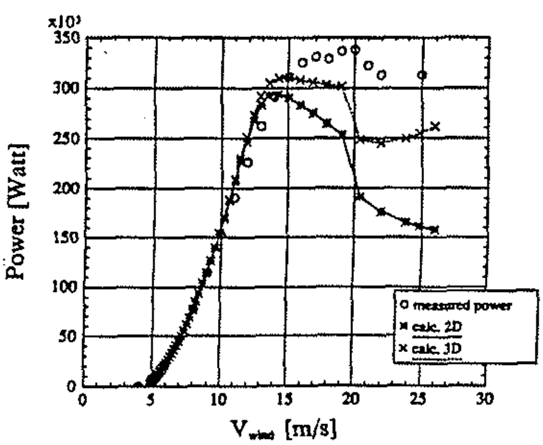

Fig.10: Calculated and measured power curves Nordtank 350 kW wind turbine.

8. CONCLUSIONS

A review has been given of recent research on the aerodynamics of wind turbine rotors. The following subjects were covered in extenso:

- The induced velocity field of rotors, including dynamic inflow and yawed flow effects.

- Stall delay on rotating blades. A new boundary layer formulation was outlined applicable to this phenomenon.

Without any further discussion, also some references have been given concerning recent wind turbine research on:

- simulation methods of atmospheric turbulence,
- dynamic stall effects, comparisons between theory and experiments,
- Effect of several types of blade tips on radiated noise.

As far as dynamic and yawed inflow is concerned, it is concluded that qualitative understanding is reasonable. "Engineering models" as well as very sophisticated computer methods are now available, and the prediction tools have been subjected to a fair amount of experimental validation. The models are in general capable of providing useful engineering estimates.

At the same time, the comparison with experiments has revealed that there are also a few fundamental problems to be solved yet:

- Even the most classical blade-element analyses are not always reliable, perhaps due to more basic, conceptual problems. These problems might be related to the way in which blade element considerations are usually combined with inflow models like momentum theory, "Pitt & Peters", or "vortex tube" models.

- The hope that sophisticated computer methods for free-wake analyses already have improved this situation is not yet fulfilled.

Thanks to recent theoretical work on rotating boundary layers, a good qualitative understanding now exists of stall delay. For reliable calculations to be made, higher order terms will probably have to be added.

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