Aerodynamics and aeroelastics of wind turbines are presented. First, the basic results of analytical, numerical and experimental work are reviewed, then the impact on commercial systems is discussed. A short section on non-standard wind turbines is finally included.

1 Introduction

Aerodynamics is a necessary tool for modeling the loads and power output of a wind turbine. Unlike other related applications such as ship propellers [5] and helicopters [6], there is no comprehensive and up-to-date presentation of this important subject. The reader is given a short introduction to current knowledge. A readable review of, especially, the German efforts during the 1950s and 1960s was given by Hütter [33]. Hansen and Butterfield [26] and Hansen et al. [25] present more up-to-date reviews.

It is assumed that the inflow velocity is more or less stationary, thereby omitting turbulence as rapid variations above 1 Hz and also neglecting diurnal variation. These distinctions are meant to be in the spirit of standard regulations, as for example given by the IEC (International Electrotechnical Commission) or Germanischer Lloyd (GL). Therefore no presentation of wake aerodynamics is found in this chapter. The interested reader may find a review of these items in [64]. This rest of this chapter is divided into seven sections.

Section 2 gives an account of analytical theories developed largely before the emergence of digital computers, beginning with the global momentum theories of Rankine [43] and Froude [23]. Several developments and extensions of these have emerged only recently. Section 3 introduces the most important development of the late 20th century: computational fluid dynamics (CFD). Therefore the reader should be familiar with the basics of fluid dynamics [2,3] and viscous fluid flow [4], together with some of the basics of CFD. Section 4 is devoted to experimental...
work on wind turbines. Two distinct branches can be identified: so-called free-field experiments, carried out in the open air and those performed under controlled inflow conditions within wind tunnels. Considerations are restricted to NASA-AMES blind comparison experiment and the European MEXICO (Measurements and Experiments in controlled conditions) project, performed in Europe’s largest wind tunnel in the Netherlands. After describing aeroelastics in Sections 5 and part 6 in general, the impact of this elaborate scientific work on commercial wind turbines is presented. This is a somewhat difficult and delicate task, as most of this work and even the results are confidential. In practice, this means that only public-domain work and non-standard turbines will be considered. Section 8 concludes this discussion with a summary and an outlook for future developments after the aerodynamics of some unconventional turbines are presented in Section 7.

2 Analytical theories

The first work which provided a simple complete model of the global flow around a wind turbine is the so-called actuator disk (AD) theory. It was first developed by Rankine and Froude to describe the flow around ship propellers. Figure 1 shows an overview of all possible flow states which can occur. Recently [58] it was possible to reproduce all flow states observed by Glauert from a numerical full-field AD model.

The main idea is the introduction of a slipstream (Fig. 2) behind the rotor. Energy is extracted by decelerating the inflow $v_1$ to $v_2$ at the rotor and $v_3$ far downstream.

![Figure 1: Flow states of propellers and wind turbines [12].](image)
Applying the equations of conservation of mass, energy (Bernoulli’s equation) and momentum:

\[ v_2 = \frac{1}{2} (v_1 + v_3), \]  

(Froude’s law) and

\[ C_p = 4a(1 - a^2), \]  

are obtained. \( C_p \) is the non-dimensional power

\[ C_p := \frac{P}{(\rho/2)Av_1^2}. \]  

\[ A = \frac{\pi}{4} D^2. \]  

A turbine of diameter \( D \) has a swept area of \( A = (\pi/4)D^2 \). The most important parameter in eqn 2 is the so-called axial interference factor \( [12] \) often also called velocity induction \( a = v_2/v_1 \). Differentiating eqn 2 with respect to \( a \) one can easily show that maximum energy is extracted when \( a = 1/3 \) and \( C_p = C_p^{Betz} = 16/27 = 0.59 \). This law was found independently by Lanchester in 1915 and Betz in 1925. Using the same arguments the main force on the turbine, the thrust in the wind direction:

\[ C_T = \frac{T}{(\rho/2)Av_1^2}. \]
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It is seen to be $c_T(a) = 4a(1-a)$ at Betz' value of $a_{Betz} = 1/3$, $c_T(a = 1/3) = 8/9 \approx 0.9$. This shows that a wind turbine is heavily loaded at the optimum condition.

The following limitations apply to the theory:

- it is implicitly assumed that there is no slipstream as there are no radial components
- calculation of the full details of the slipstream expansion cannot be performed as the theory does not consider the radial velocity component
- the axisymmetric disk is assumed to be infinitesimally thin.

As already discussed by Betz [9] and further by Loth McCoy [70] in the context of a double AD for vertical axis wind turbines there is a possibility to beat Betz to some extent (roughly to 0.64 for a double AD). A recent discussion for beating Betz with general devices was given by Jamieson [34].

Wind turbines are rotating machines, and a very important dimensionless number is the tip speed ratio (TSR) defined as

$$\lambda = \frac{\Omega R}{v_{wind}}$$

where $\Omega$ is the angular velocity of the turbine.

Figure 3 gives a graph of various $c_p$ against $\lambda$. Apart from its own data, data from the classical literature, for example [14,18], was also included. Two items are
Aerodynamics and Aeroelastics of Wind Turbines

of particular interest. Firstly, all turbines have a maximum $c_p$ and two kinds of turbine can be distinguished, those with a maximum $c_p$ around 6–10 (so-called fast running machines) and those with maximum below 4 (so-called slow running machines). Secondly the curve must tend towards $c_p = 0$ when $\lambda = 0$. This was discussed by Glauert [12] and stems from the fact that in addition to the axial induction $a$, a second $a'$ has to be introduced, where $a'$ is defined by

$$a' = \frac{\omega}{2\Omega}. \quad (7)$$

Here $\omega$ is the local angular velocity of the flow. It comes from Newton’s third law as applied to angular momentum. If $dr$ is an increment of radius, the torque is now

$$dM = 4r^3 v_1 (1 - a) a' \, dr \quad (8)$$

and the total power becomes

$$c_p = 8\lambda^2 \int_0^1 a' (1 - a) \left(\frac{r}{R}\right)^3 \, d\left(\frac{r}{R}\right). \quad (9)$$

The two parameters $a$ and $a'$ have to be optimized. A third equation, the so-called orthogonality condition of Glauert [12] is the condition

$$a' (1 + a') x^2 = a (1 - a) \quad (10)$$

with $x = \omega r / v_1$ being the local TSR. Figure 4 gives a sketch of the arrangement of the velocity vectors. Optimization results in the condition

$$a' = \frac{1 - 3a}{1 + 4a} \quad (11)$$

Figure 4: Velocity and force triangles.
which shows that $1/4 < \alpha < 1/3$ must hold. These losses as compared to Betz’ ideal limit are called *swirl* losses. Figure 5 shows the quantitative dependence. Two other mechanisms have to be introduced, to model all effects shown in Fig. 3. They are the so-called tip-losses and profile-drag losses. An AD was defined as a compact disk, formally having infinitely many blades. To estimate the effect of a finite number of blades, the two models are used. One is based on conformal mapping of the flow around a stack of plates to that of a rotor with a finite number of blades (given by Prandtl [42]) and the second is based on the theory of propeller flow of Goldstein [24]. A recent investigation has been made by Sørensen and Okulov [39,40]. Usually a reduction factor $F$ is introduced to account for the decreasing forces on the blade towards the tip:

$$ F = \frac{2}{\pi} arccos \exp \{-f\}, $$  

with

$$ f = \frac{B R - r}{2 r} \sqrt{1 + \lambda^2}. $$

$\lambda$ as expressed by eqn 6.

Comparison with measurements by Shen *et al.* [55] resulted in a new empirical tip-loss model for use in AD and CFD simulations. Recently Sharpe [53] has revised the arguments of Glauert and extended them slightly. Mikkelsen *et al.* [38] applied his numerical AD method to investigate this effect. His findings were that

![Glaeuert’s optimum rotor](image)
Figure 6: Comparison of swirl drag and profile-drag losses against measured values of actual turbines.

despite the fact that the otherwise neglected pressure decrease in the near wake gives higher $c_p$ in the inboard section, Betz' limit is valid globally.

When considering drag losses, one has to imagine that a rotor blade can be regarded as an aerodynamic device experiencing two forces drag (in flow direction) and lift (orthogonal to that). The lift force and part of the drag force (per unit span) are due to the pressure around the airfoil. Figure 7 illustrates this. The $c_p$ is defined as

$$c_p = \frac{P}{(\rho/2)v^2}$$  \hspace{1cm} (14)

where $c$ is the chord of the airfoil.

Here:

$$c_D = \frac{D}{(\rho/2)v^2 c \cdot 1}$$  \hspace{1cm} (15)

and

$$c_L = \frac{L}{(\rho/2)v^2 c \cdot 1}$$  \hspace{1cm} (16)

are defined. It can be shown that lift gives rise to no loss as it is perpendicular to the flow, which is not the case for drag. A measure of efficiency for profiles is
defined as the lift-to-drag-ratio $L/D$. Usually this number is around 100. In total Figs. 10 and 11 are obtained. Compared to Fig. 3 the quantitative influence of drag and finite bladenumber on $c_p$ are presented. In addition Fig. 6 shows the improvement of state-of-the art commercial wind turbines of one manufacturer over a span of 20 years. Clearly one can see that high-performance airfoils have to be used to reach for a $c_{p,\text{max}}$ in the order of 0.52. It is clear that $B = 1$ is very special, and one might assume that no such turbines were manufactured. This in fact was not the case. In the late 1980s the German company MBB manufactured the so-called Monopteros (see Fig. 9), a single-blade turbine. To demonstrate the big differences data from Rohrbach et al. [46] is included.

Figure 7: Pressure coefficient around an airfoil.

Figure 8: Lift and drag around an airfoil; $v$ is a sample inflow velocity and is not to be confused with a relative velocity.
Sørensen and Okulov [39,40] recently formulated a vortex theory for these types of rotors (see Fig. 11).

To sum up: at the present time a limit of $c_p = 0.52$ seems to have been reached by modern turbines, which is only possible if specially designed airfoils are used. A $c_p$ of 0.45 (typical for turbines in the early 1990s) is obtained using old profiles from the aerospace industry (see Figs 3 and 6).
2.1 Blade element theories

Blade element theory (see Fig. 9) divides the rotor into several finite length sections of $\Delta r$ (or $dr$ mentioned above). Then forces applied on these annuli are compared to those from airfoil theory. Implicitly it is assumed that there is no mutual interference of the sections. With reference to Fig. 9 and denoting with $dm$ the mass flow through the disk and with $v_t$ the tangential velocity, a thrust
\[ dT = \delta m(v_1 - v_3), \]  
\[ dT = 4a(1 + a)2\pi r dr \frac{\rho v_1^2}{2}, \]  
and torque \[ dQ = \delta m v_r, \]  
\[ dQ = 2\pi r dr \rho v_2^2 2\pi r^2, \]  
\[ dQ = 4\pi r^3 \rho v_3 \Omega(1 - a)\alpha'. \]

increment is obtained.

Now comparison with the forces resulting from the airfoil sections is performed. From Fig. 8 the force coefficient in the inflow direction is

\[ C_N = C_L \cos(\alpha) + C_D \sin(\alpha). \]  

Here the flow angle \( \varphi \) can be computed from the velocity triangle.

\[ \tan(\varphi) = \frac{(1 - a)v_1}{(1 + a')\alpha}. \]  

The angle of attack and the flow angle is related via the twist angle \( \varphi \):

\[ a = \varphi - \varphi. \]  

The square of the velocity is \[ w^2 = ((1 - a)v_1)^2 + (\omega(1 + a'))^2. \]

All relevant data is then calculated using an interaction scheme. It is to be noted that in the inner part of a blade, values of greater than 0.5 and even 0.52 are observed. Then the simple momentum theoretical value \( c_T(a) = 4(1 - a)\alpha \cdot a \) is no longer valid. An empirical extension for \( 0.5 < a < 1.0 \) must be used. The deviation starts at \( a = 0.3 \) and gives \( c_T(a = 1) \) of approximately 2.

Many engineering codes, such as the PROP Code of Walker and co-workers [18] follow this approach. These codes rely heavily on measured aerodynamic data for airfoils. In the early days of wind energy, airfoils from ordinary airplanes were used. Since then, special airfoils for wind turbines have been developed, mainly at Stuttgart (FX-Series), Delft (DU profiles) and Risø. Today, not only power optimization but also load reduction has to be included into profile and blade design. Another important issue is a phenomenon called stall delay within rotating boundary layers. Since its first observation by Himmelskamp [30] in 1945, it has become evident that much behavior cannot be explained without the phenomenon, which is also important for swept flow. For 3D boundary layers the ECN model [45]:

\[ f = 3\left(\frac{c}{r}\right)^2 \]  

with \( f \) defined as \( C_{L,3D} = C_{L,2D} + f(2\pi\alpha - C_{L,2D}) \) is often used.
2.2 Optimum blade shape

Neglecting drag all relevant forces can be derived from lift via (compare to Fig. 9)

\[
\frac{dT}{dr} = Bc \frac{\rho \omega^2}{2} C_L \cdot \cos \phi \tag{27}
\]

and torque

\[
\frac{dQ}{dr} = Bc \frac{\rho \omega^2}{2} C_L \cdot \sin \phi \cdot r. \tag{28}
\]

Adding to eqn (10) the momentum balance for thrust, equation (17), and torque equation (19) solution for \( a \) and \( a' \) is possible. The following final equations are obtained:

\[
\frac{a}{(1-a)^2} = \frac{\sigma C_L \cdot \cos \phi}{4 \sin^2(\phi)} \tag{29}
\]

\[
\frac{a'}{1+a'} = \frac{\sigma C_L}{4 \cos \phi} \tag{30}
\]

With \( \sigma = BC/2\pi r \) solution for \( c \cdot C_L \) which is proportional to the circulation:

\[
\frac{Bc\sigma C_L}{2\pi v_i} = \lambda, \sigma C_L = \frac{4 \sin(2 \cos \phi - 1)}{1 + 2 \cos \phi}, \tag{31}
\]

can be performed. Division by \( r/R = \lambda / \lambda R \) results in the desired ratio \( c/r \) against \( r/R \) (Fig. 13). Together with Glauert’s theory the more extended approach of Wilson [18] and De Vries [17], which includes also the lift to drag ratio and tip losses:

\[
\frac{(1-aF)aF}{(1-a)^2} = \frac{\sigma C_L \cdot \cos \phi}{4 \sin^2(\phi)}, \tag{32}
\]

\[
\frac{a'F}{1+a'} = \frac{\sigma C_L}{4 \cos \phi} \tag{33}
\]

with \( F \) from eqn 12 is obtained. It can be seen that for \( C_L/C_D = 100 \) and \( B = 3 \), there are only small differences from the Glauert theory. Recently [40] it was found that the widely used optimization approach by Betz may be overcome by the older one of Joukowsky [36] thereby stating that a constantly loaded rotor with a finite number of blades may be superior to that with a Betz-type load distribution.
3 Numerical CFD methods applied to wind turbine flow

As a complement to analytical theories and experiments, CFD provides a third approach in developing applied methods. In its purest form, only the differential equations of Navier and Stokes (NS):

\[ \nabla \cdot \mathbf{v} = 0, \quad (34) \]

\[ \rho \frac{D\mathbf{v}}{Dt} = -\nabla p + \mu \Delta \mathbf{v} = 0 \quad (35) \]

together with suitable boundary conditions and a description of the blade geometry is used. Unfortunately this ambitious goal cannot be reached at the present time. The main obstacle is the emergence of turbulence at higher Reynolds number (RN):

\[ Re = \frac{vL}{\nu} \quad (36) \]

calculated from kinematic viscosity \( \nu = 1.5 \times 10^{-5} \text{ m}^2/\text{s} \) for air) and a typical length \( L \) and a typical velocity \( v \). Present wind turbines have a RN of several million based on blade chord. Only Direct Numerical Simulation (DNS) solves the (NS) without any further modeling. At the present time (2009), only airfoil calculations up to RN of a few thousands have been carried out at the price of months.
of CPU time and terrabytes of data. After Large Eddy Simulation (LES), the next stage of simplification is Reynolds averaged Navier Stokes equations (RANS). An ensemble average, which is assumed to be a time average by an ergodic hypothesis is carried out for all flow quantities.

Turbulence then emerges as a never ending hierarchy of higher correlations which has to be truncated by the so-called closure assumption. In wind-turbine applications at the present time the \( k – \omega \) shear stress transport (SST) extension of Menter is frequently used. \( k \) is the turbulent kinetic energy (per unit mass) and \( \omega \) is a local frequency scale. Unfortunately all these empirical turbulence models describe only fully developed turbulent flow and are not able to resolve the transitional region from laminar to turbulent flow. There are good reasons to believe that parts of the blade must be laminar because otherwise the large L2D ratio cannot be achieved for \( c_p \) of the order of 0.5.

At UAS Kiel from 2000–2003 a program [65] comparing 2D-CFD simulation with measurements was carried out. A 30% thick airfoil from Delft University was chosen: DU-W-300-mod. For including transitional flow properties to \( e^N \)-method of Stock was included in DLR’s structured CFD-Code FLOWer. The main findings of this project were as follows:

- Mesh generation with mostly orthogonal grids is very important. Therefore a hyperbolic type of generating equation, namely

\[
x_\xi x_\eta + y_\xi y_\eta = 0, \tag{37}
\]
\[
x_\xi y_\eta - y_\xi y_\eta = \Delta A. \tag{38}
\]

was chosen. For details see [62].

- The \( e^N \) method has to be parameterized with an \( N \) (usually between 6 and 9) which is related to a surrounding turbulence intensity by Mack’s correlation. Comparison with wind tunnel measurements was difficult because the turbulence intensity was not known exactly.

- Prediction of \( c_{L,\text{hit}} \), meaning computation of flow separation (stall) was also difficult, because the flow started to become unsteady.

- Transition points were predicted correctly as long as only laminar separation or Tollmien Schlichting (TS) instabilities triggered transition.

- In addition, drag effects for example from Carborundum or Zig-Zag band were difficult to predict [28].

The situation becomes more complicated when whole blades are investigated. Correct prediction of overall power curves is seen to be very difficult. The picture is uneven [37] but parametric studies such as for wings including winglets [35] give valuable insight into the flow field and comparative changes. This is especially important when discussing performance enhancements.

Much better results can be achieved when no turbulence has to be included in the discussion. This is always the case, when basic studies have been performed.
which cannot easily be checked by hand calculations. An example of such methods are the modification of the AD and actuator line method initiated by J. Sørensen and further developed by R. Mikkelsen. Another promising field of application is site-assessment and wind-farm optimization. The second torque conference at Copenhagen in 2007 gives an impressive report of the progress which has been made in this field. One has to bear in mind that the usual problems with turbulence modeling are the same as in other fields mentioned above.

4 Experiments

4.1 Field rotor aerodynamics

From 1992 to 1997, the International Energy Agency (IEA) conducted large-scale comparisons of measurements on research-type wind turbines. The project was termed Annex 14 [52] and was designed to

- validate and develop design codes,
- investigate design principles for stall controlled turbines.

Five turbines from ECN in the Netherlands, IC/RAC in the UK, NREL in the USA, RISO in Denmark and DUT in the Netherlands were considered. The diameter ranged from 10 to 27 m. The profiles used were quiet diverse, ranging from the NACA 44xx and NACA 632xx to the NLF 0416 and the S809. One objective was to investigate the correlation of measured performance and 2D-profile data from wind tunnel measurements.
As a result many problems with consistent interpretation of all the data were identified. Especially the definition of a local angle of attack was very difficult. This of course is also the case when 3D-CFD investigations are discussed. Several approaches have been tried, one being a correlation between the location of the stagnation pressure line and AOA. A second is the so-called inversed BEM, where $c_N$ and $c_T$ are correlated to the local flow angle. One may object that both methods rely on 2D assumptions for connecting forces and velocities so they may fail when 3D effects are strong. A somewhat detailed review is given by van Rooij [45] and Shen et al. [54]. It may be useful to note that a new program subsequent to the above-mentioned experiments will be started in early 2009 which will be undertaken on the research wind turbine E30 at the University of Applied Sciences Flensburg. During this experiment, using an aerodynamic glove, shear stresses which indicate the state of the boundary layer (laminar, transitional or fully developed turbulent) will be measured for the first time [51].

4.2 Chinese-Swedish wind tunnel investigations

In a joint effort of Chinese and Swedish aerodynamicists, a 4.75-m diameter wind turbine was investigated in the late 1980s [21, 44].

4.3 NREL unsteady aerodynamic experiments in the NASA AMES-wind tunnel

As a result of the rather disappointing findings from open air experiments a big effort was mounted by NREL, the US National Renewable Energy Laboratory. A 10-m diameter two-bladed rotor was put into the world’s largest wind-tunnel, the NASA-AMES wind tunnel located in California. The main advantage was a complete control over all inflow conditions. Most important was the so-called blind comparison in which a variety of design and analysis tools were used to predict the power and forces based on 2D data. Figure 15 gives an overview of all simulation for the shaft torque, which is proportional to the power, see [56] for broad discussion. Several important conclusions can be drawn from the results of this large-scale experiment:

- 10 tested aeroelastic codes (see Section 5) showed extremely large disagreement even in the attached flow regime. The measured low-speed shaft torque being 800 Nm, is scattered in the predictions from 200 up to 1400 Nm (factor of 7). This situation is only a little bit better at 10 m/s (30%) but became worse at the same level as before in the deep-stalled case.
- So-called performance codes (only three, being descended from the famous PROP Code) showed strong variations in the deep-stalled condition with one remarkable exception which gives almost the same result as one CFD investigation.
- Two wake codes give also non-uniform results.
- Most impressive were the CFD results of Sørensen [59]. There, without any 2D-profile data, results with the same degree of accuracy of the best BEM
simulation (probably M. Hansen and T. Chaviaropoulus) were obtained. The effort was still rather expensive: 3M cells and about 50 h CPU on a 4-processor machine. Later Sørenesen [60] also introduced also transitional effects but with limited success.

4.4 MEXICO

The European answer to the NREL experiment was a model experiment in controlled conditions. The large-scale facility of DNW of $9.5 \times 9.5 \text{m}^2$ open section was used [57]. A complete analysis is to be worked out within the new established IEA Annex 29 MexNext, where scientists from several countries outside Europe will also participate. Most important is the additional measurement of the velocity field by Particle Image Velocimetry (PIV).

5 Aeroelastics

5.1 Generalities

Wind is transformed into forces by striking the solid structure of the blades. These are manufactured by regarding them as aerodynamic devices. Lift, drag and pitching moment result from the combined flow of wind and rotating flow. These forces now act on a flexible structure. The interaction of aerodynamics and structural mechanisms is called aeroelastics. As turbines become larger they necessarily

![Figure 15: Blind comparison of shaft rotor torque of various predictions against measurement.](image)
have to become lighter, meaning that their lowest eigenfrequencies approach a
certain limit. This limit is usually given by the excitation frequency of the rotor
multiplied by the number of the blades. Therefore a model has to be constructed
which includes both aerodynamics and structural dynamics.

Different stages of sophistication have to be identified

I Aerodynamic
1. Blade Element Momentum Code (BEM)
2. Wake Codes
3. Full 3D-CFD including turbulence modeling

II Structural Mechanics
4. Beam (1D) model
5. Shell (2D) model
6. Solid (3D) model

In principle 3 · 3 = 9 possibilities for coupling the various methods can occur. At
the present time (1 with 4) coupling is one of the most commonly used in industry.
Several industrial codes are available, some of which are:

• FLEX, from Stig Øye, DTU
• BLADED, by Garrad Hassan
• GAROS, by Arne Vollan, FEM
• Phatas, by ECN

and many more.

There are several difficulties in improving the accuracy of this approach. Beam-
like parts of the turbine, like the tower and blades are easy to fit into the BEM Code.
Not so easy to include are major parts of the the drive train, gear-boxes and the elec-
tromechanical parts such as generators. Also control systems which are used more
and more to decrease loads have to be included. So in the forseeable future, coupling
between more or less standardized and specialized software systems will be seen.
Examples may be MATLAB/Simulink for electrical control, flexible coupling of
multi-body systems like gear-boxes and shafts with standard FEM tools like ANSYS
or MSC NASTRAN, to name only a few. From fluid mechanics it is not easy to see
how BEM can be improved. CFD is rather time consuming and not a priori better
when BEM is improved by empirical enhancement. At the present time, coupling of
types (3 with 5) or (3 with 6) is the subject of ongoing research.

5.2 Tasks of aeroelasticity

By far the most important task of aeroelasticity is certification or type-approval.
Most operators of wind-farms can only finance, operate and insure their turbine
when appropriately certified. Usually during this process many aeroelastic load
cases have to be simulated. They are documented within rules or guidelines.
Some of the tasks are to:

- ensure safety against aeroelastic instabilities such as divergence/flutter,
- investigate loads from extreme events expected only a few times within the estimated lifetime,
- accumulate the effects of loads from rapidly changing operating conditions during normal or electricity generation.

A turbine may be called optimized if it can resist equally against extreme winds and fatigue loads. Because a detailed description of recent procedures is rather exhausting to the beginner, he or she may start with a somewhat out-dated but classical text: *Wind turbine engineering design* by Eggleston and Stoddard [76]. There the reader will find a clear description of how the basic physics together with engineering requirements may be fit together in a computer code. A recent review more closely to pure aeroelastics was given by Hansen et al. [25]. On the other hand, it is worth noting how classical aeroelastics (usually coming from airplane design) now re-enters into recent wind turbine design for offshore applications [19].

### 5.3 Instructive example: the Baltic Thunder

Presenting a whole aeroelastic case study is far beyond the scope of this short introduction. Here it is tried to exemplify a description in a somewhat different way. In 2008 a Dutch organization called for a competition for a wind driven car for the first time. Six teams from four countries presented their design, one of them was the Baltic Thunder (see Fig. 16). Because one goal was to reduce parasitic drag as much as possible, the weight had to be reduced as far as possible. A light but flexible structure was the result. For other reasons a vertical axis rotor was chosen (see Section 7.1). This rotor is known to be particularly prone to aeroelastic instabilities. Therefore a Campbell diagram was produced by Volland’s Code GAROS. Due to the soft blade suspension a vertical bending mode of about 2.5 Hz was not to be avoided. This gives rise to a flutter type instability at 500 RPMs. Therefore the final design had carbon reinforced fiber (CRF) tubes as suspension giving much higher first blade eigenfrequencies. One of the various safety proofs included safety against a 18 m/s gust when operating in normal mode. Figure 18 shows the response of the main rotor tower. A static (constant) force of about 700 N superimposed on the dynamic response of the RPM excursion from about 200 to 300 RPM only. It has to be noted that a 18 to 12 m/s increase of wind speed is equivalent to an increase of power by factor of 3.4 if $c_p$ remains constant. In this case maximum force excursion is only up to 1200 N so that at least the central column could be regarded as safe.

### 6 Impact on commercial systems

#### 6.1 Small wind turbines

In general it is hard to see what effect the impact of scientific work will have on a specific commercial product. On the one hand, there is a huge number of engineering
Figure 16: Photograph of the Baltic Thunder wind driven vehicle prepared for the Racing Aeolus challenge at Den Helder, The Netherlands, August 2008.

Figure 17: Campbell’s diagram and wind gust.
experts working in large companies and on the other hand real testing is possible only for small wind turbines. An overview of small wind turbines is given first. According to IEC, small WTs have a swept area smaller than 200 m². This gives a diameter of less than 17 m. Sometimes a subclass of WT which have swept area even less than 40 m² are also considered. These turbines have a diameter of 7 m or less. The main problems for these turbines are the manufacturing costs and a comparable aerodynamic performance to their larger relatives. Due to Reynolds number effects, the $C_p^{max}$ of small wind turbines is approximately 0.3 instead of 0.5 for the best standard (2–3 MW) commercial turbines. This is mainly due to the much lower $L_2D$ ratio at Reynolds numbers below $10^5$. Thus several attempts have been made to find thicker (> 10%) profiles giving a better performance. See Figs 19 and 20 for examples.

Further information can be found in [63].

6.2 Main-stream wind turbines

It is obvious that most efforts have been made to optimize so-called main-stream wind turbines with several MW rated power but below 3 MW. The author [50] was able to compare measurements of three different blade sets (see Fig. 21) on the same machine. Although the tip-speed ratio was 8.5 for one blade and only 7 for the other blades the $C_p^{max}$ difference varies from 0.49 to 0.46 resulting in an improvement of 6%. As a conclusion this shows that dedicated or tailored profiles and blades can improve the performance significantly. $C_p^{max}$ currently seems to have settled down at around 0.52 for the best turbines as to be expected from the discussion in Section 2.

New developments therefore aim to reduce loads without losing power. This can be achieved by reducing $C_L^{max}$ against $C_L(L2D – max)$. In contrast a safe distance to $C_L^{max}$ also prevents early stalling. During the 1990s a lot of new aerodynamic profiles were investigated in the US (Seri), in Delft (DU) and at Risø (Risø A,B...
and P-series). As already and often mentioned, this has led to a $c_p^{\text{MAX}}$ close to the theoretical maximum.

### 6.3 Multi MW turbines

Since around 2000 the off-shore use of wind energy has progressed, one of the first being the wind farm Middlegrunden close to Copenhagen, which started operation in 2000. It soon became clear that, due to the narrow time frame available to reach the wind farm off-shore, they have to be much larger than usual wind turbines. Especially in Germany the development of so-called Multi Megawatt turbines has started, these now reaching 6 MW rated power. In this connection several questions arise. Do the aerodynamic properties stay the same when upscaling the blades?
The Reynolds number of a 63-meter length (REpower 5M) blade may reach 6 million and more. A major project was started in 2002 at the UAS Kiel to measure the aerodynamic properties of a 30% thick slightly modified Delft profile [22,61,65]. As an outcome a variety of aerodynamic devices were measured as well as polars up to 10 million. This was achieved by cooling down the tunnel gas to only 100 K (= –173°C). Figs 22–24 give an impression of the results achieved so far. An attempt to model the results numerically are reported in [49].

7 Non-standard wind turbines

7.1 Vertical axis wind turbines

Two kinds of unusual turbines are discussed briefly below as further examples of the application of aerodynamics to wind turbines. The first example is a wind...
turbine with a vertical axis of rotation (VAWT) and the second are diffuser augmented wind turbines. A discussion of counter-rotating systems is omitted here. The reader may find information in [48, 32].

Two types of VAWT are possible (see Fig. 25): those driven by drag (Savonius) and those driven by lift (Darrieus). Aerodynamic modeling starts with the question whether an actuator disk modeling makes any sense. The total structure is an extended one, so at least two disks for up-wind and down-wind halves have to be used. This double actuator disk model was formulated by Loth and Mc Coy [70]. Only circumferential averaged values are discussed. The usual momentum theory for two independent disk was applied. As a result of these assumptions only one optimization parameter $a$ – the (global) velocity interference factor – remains, giving $C_p^{\text{max,dAD}} \approx 0.64$. Further, the power extraction is seen to split into 80 and 20% shares for the first and second disk respectively.

Figure 26 shows the findings in a graph. It is stricking that the total (normalized) power is >0.6 along the range $0.1 < a < 0.42$. Here $a$ was defined as usual as $a := v_{\text{disk}}/v_{\infty}$. It should be noted that such high $C_p$s have not been observed so far. As an important design parameter the solidity $\sigma = Bc/R$ ($B =$ number of blades; $c =$ chord and $R =$ rotor radius) is used. It can easily be shown that low $\sigma$ corresponds to high TSR but unfortunately then there is no self-starting [67] behavior. Only when using high $\sigma \geq 0.4$ can a self-starting turbine be achieved.
Figure 25: Vertical axis wind turbines.

Figure 26: $c_p(a)$ for a double actuator disk.

Figure 27 shows a comparison between various methods of calculating $c_p$. The first method [18] uses a simple procedure for the induced axial velocity which then is a function of circumferential angle $\phi$. To simplify matters this is assumed to be $a(\phi) = \lambda a/2 \sin(\phi)$. This method results in a $c_{p_{\text{max}}}$ which is only slightly smaller than $c_{p_{\text{Betz}}}$. Holme’s [66] method uses a vortex approach to describe the flow field. Here the unsteadiness was avoided by distributing the bound circulation around a whole circle. This then gives a steady but non-symmetric model which also makes it possible to calculate transverse forces. Figure 27 shows, however, only minor changes to the first method, that of Wilson [18]. A simple blade element method was formu-
lated by Stickland [74] in the 1970s. Here the the flow is divided into various stream tubes and an internal computer code interaction ensures the actual balance of axial momentum. As a result of including drag the $c_p$(TSR) curve now becomes much narrower and the maximum also decreases to values common for HAWTs. In addition CFD methods can be applied to VAWT. To avoid time-consuming unsteady computations a special technique called interface averaging between two computational volumes with different frames of references were used. One volume in the vicinity of the rotor experiences inertial forces due to rotation. The delicate point now is how to pass over to the second volume where no inertial forces are applied. In summary a much smaller $c_{p\text{max}}$ may be predicted by this method. Meanwhile [71] 3D transient CFD simulation have been carried out.

Further research is obviously necessary to reduce the large differences obtained by the various methods. It should be noted that manufacturers of small wind turbines try to use the vertical axis principle again. Unfortunately no particular system seem to be able to compete against HAWT. This is mainly because most systems do not possess a dynamically stable supporting structure.

7.2 Diffuser systems

Wind-concentrating systems such as shrouds, ring-wings and diffusers have been being investigated for a period of about 50 years. A summary has been given by van Bussel [20], together with a 1D momentum theory and a collection of experimental data. Special emphasis has been given to a discussion of the influence of the diffuser’s exit pressure. It should be noted that most of the designs try to use a
large input–output area ratio, whilst being relatively short. A permanent danger is the early separation of air flow through the diffuser as can be seen from Fig. 28 [41,47], where a relatively short diffuser was designed for an area ratio of approximately 3.

The author does not agree that a final theory has been formulated in which the specific problem has been solved. It may be necessary to extend the work of Loth and McCoy [70] who discussed an array of disks as a model of an actuator volume to a real continuum theory. This is an important task because a safe upper limit, such as Betz’ law, is important for all investigations. A successful commercial design has also not been produced so far.

8 Summary and outlook

The history of wind turbine aerodynamics spans approximately 150 years. The most important influence has been given by modelling flow properties which then serve as tools for predicting loads on the structure. As a consequence safe and competitive wind turbines up to rated power of 6 MW have been constructed so far. First investigations of even larger blades feasible for rated power up to 10 MW are under consideration [29].

Further progress can be expected when CFD when taken in the strict sense of the expression as solving the Navier-Stokes equation without any further assumptions enters the usual design process in companies. Nevertheless full-scale experiments in wind tunnels and outdoors are equally as important as analytic theories.

Figure 28: Sketch of the separation of flow through a short diffuser.
References


