Chapter 6

Loads and Structural Stresses

Wind turbines are subjected to very specific loads and stresses. At a first glance, the main problem appears to be the stability in heavy storms and hurricanes. However, the continuous alternating loads - even under normal wind conditions - are just as problematic. Alternating loads are more difficult to cope with than static loads because the material becomes "fatigued".

The dimensions of the components present a further problem. As a working medium, the air is of low density so that the surfaces required for converting energy must be large. If the dimensions of the rotor increase, the dimensions of other components must also increase, for example the tower height. Large structures are inevitably elastic and the changing loads thus create a complex aeroelastic interplay which induces vibrations and resonances and can produce high dynamic load components.

The structural dimensioning of a wind turbine must be considered under three different aspects:

Firstly, attention must be paid to ensuring, from the point of view of breaking strength, that the components are designed for the extreme loads encountered. This means in real terms that the turbine and its essential components must be able to withstand the highest wind speeds which may occur.

The second requirement is that the fatigue life of the components must be guaranteed for their service life, as a rule 20 to 30 years. While the stresses with respect to extreme loads can be estimated relatively easily, the problem of "fatigue life" is virtually the key issue with wind turbines. Wind turbines are the perfect "fatigue machines"!

The third aspect concerns the stiffness of components. On the one hand, structures with elastic properties reduce fatigue, but on the other hand, external excitations produce vibrations in elastic components. The vibration behaviour of a wind turbine can be kept under control only when the stiffness parameters of all its components are carefully matched in order to avoid hazardous resonances and additional dynamic loads. Dynamic loading on the wind turbine unavoidably does exist due to the changing external loads but it should not be amplified by a critical vibrational behaviour of the components.

An important set of problems, even before the structural design loads are calculated, concerns the loads to be stipulated and the situations in which the loads occur which determine the dimensions of the structure. This requires a complete overview of all external operating conditions and of possible malfunctions of the turbine. On the basis of this, the so-called *load cases* can be defined. However, the real loads to which the wind turbine is subjected can never be covered in their entire complexity which is why they can always be stipulated only in an approximated, idealized form as *design loads*. The *load assumptions,* i.e. the load cases with the loads form an important basis in the design process. The mathematical methods needed for calculating structural loads and material stresses include some of the most complex theoretical tools required for developing wind turbines. The models are basically not different from those used in other fields of technology. Nonetheless, the course of action to be taken in relation to the structural design of a wind turbine is governed by its own set of problems.

The starting point for the entire load spectrum of a wind turbine are the loads acting on the rotor. The loads on the rotor blades are passed on to the other components and to a great extent determine their loading. Compared to these loads, the loads originating directly from downstream components are less significant. Discussions of the loads acting on a wind turbine can, therefore, be concentrated on the rotor and deal with it as being representative of all parts.

6.1 Loads on the Wind Turbine

The causes of all forces acting on the rotor are attributable to the effects of aerodynamic, gravitational and inertial forces. The different loads and stresses can be classified according to their effect with time on the rotating rotor (Fig. 6.1):

- Aerodynamic loads with a uniform, steady wind speed, and centrifugal forces, generate time-independent, steady-state loads as long as the rotor is running at a constant speed.
- An air flow which is steady, but spatially non-uniform over the rotor-swept area causes cyclic load changes on the rotating rotor. This includes, in particular, the uneven flow towards the rotor due to the increase in wind speed with height, a cross-flow towards the rotor and interference due to flow around the tower.
- The inertia forces due to the dead weight of the rotor blades also cause loads which are periodic and thus unsteady. Moreover, the gyroscopic forces produced when the rotor is yawed must also be included among those which increase or alternate with each revolution of the rotor.
- In addition to the steady-state and cyclically changing loads, the rotor is subjected to non-periodic, stochastic loads caused by wind turbulence.

For an investigation of structural stresses, it is important to consider the effects of load variations with time. Fluctuating and alternating loads must be recognized, especially with respect to the fatigue life of the structure. Extreme loads in specific situations have to known to ensure the survival of the structure with respect to ultimate stress.

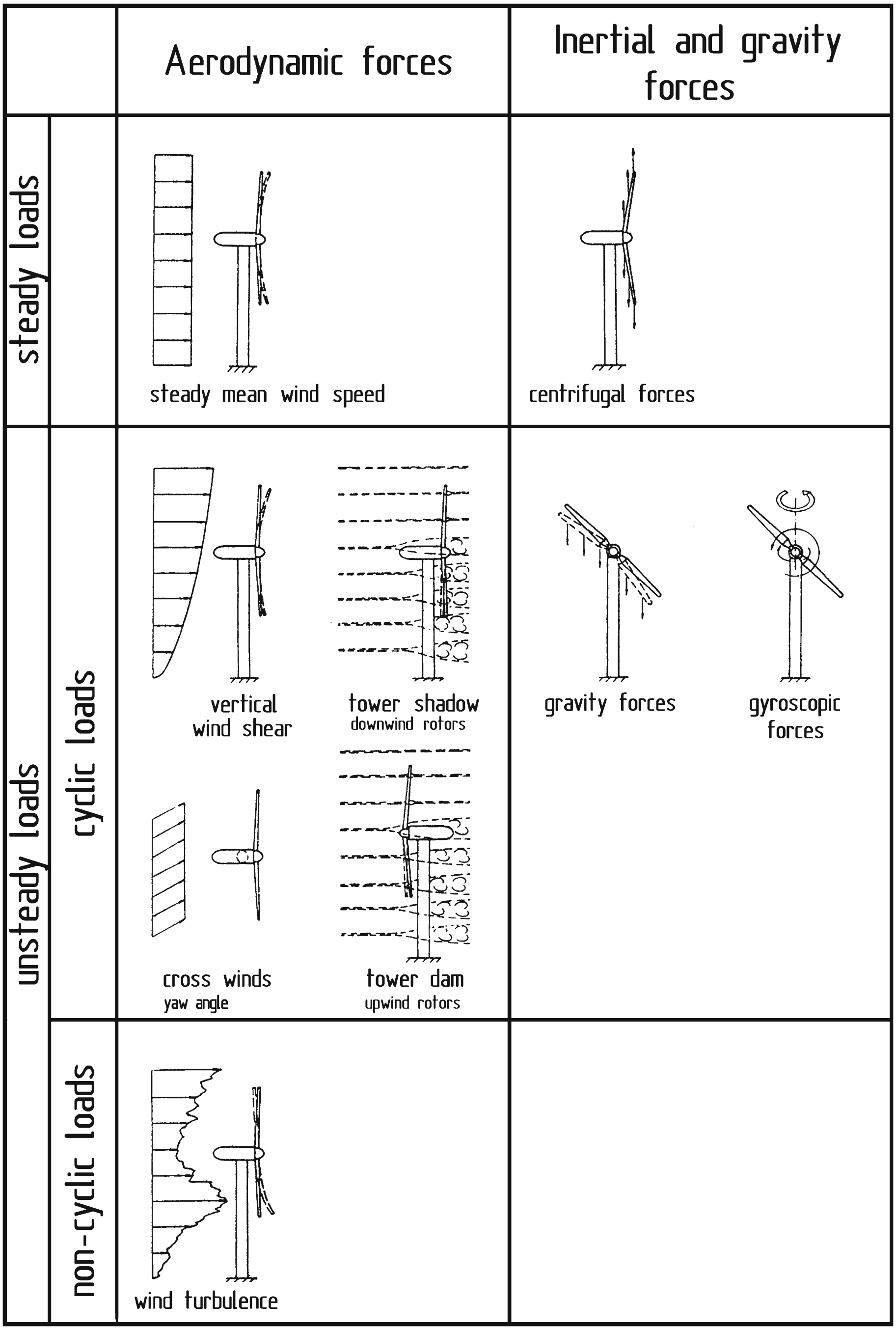

Fig. 6.1. Effect of aerodynamic, gravitational and inertial loads of the rotor of a horizontal-axis wind turbine

It is not possible to recognize beforehand which of the loads within the entire range of loads will be dominant. As is the case in all structures, the larger the turbine, the greater is the significance of the gravitational loads. Moreover, the elasticity of the structure plays an increasing role with respect to the extent to which the external loads are transformed into structural stresses. For example, the speed variability of the rotor or the elasticity of the rotor blades are of significance for the extent to which the external loads are converted into structural stresses.

In other words: apart from the external loads, the load level is also determined by the design of the wind turbine. In general it holds true that the more elastic the structures are, the better alternating loads can be absorbed and thus material fatigue can be reduced, but on the extreme end, the flexibility of the structure causes vibration problems, and not lastly the mathematical effort increases with increasing elasticity in the dimensional design of the structure.

6.2 Coordinate Systems and Terminology

Unfortunately, there is to the present day no legally binding standard for the position and orientation of the coordinates in which the load parameters are represented. The same also applies to the terms to be used for the parameters. In English usage, the designations used in IEC Standard 61400-1 have gained currency without being legally binding in the sense of a Standard [1]. In German usage, many other terms are also commonly used and in the German edition of this book older German expressions are also used and their English equivalents are referred to only occasionally.

It would be confusing if one would try to put all the parameters and figures in one common co-ordinate system. Already the very different order of magnitude of the various values speaks against it. Therefore to represent the loads on the rotor and the structural stresses, three co-ordinate systems are suitably used (Fig.6.2).

The forces and moments acting on the rotor blades are resolved in a rotating co-ordinate system with respect to the local rotor blade cross-section. In the direction of the airfoil chord, the "chordwise" component is obtained and perpendicularly to the airfoil chord it is the "flapwise" component. This approach is practical when the loads on the rotor blades themselves are considered.

The breakdown with respect to the plane of rotor rotation provides the "tangential force components" in the plane of rotation and the "thrust components" perpendicularly to the plane of rotation. These co-ordinates express the total forces and moments on the rotor when they are passed on to the remaining parts of the turbine in the form of loads. At the transition from the chordwise and flapwise directions of the blade to the tangential and thrust directions of the rotor, the local twist angle and the blade pitch angle must be taken into consideration.

A third system of co-ordinates has its origin at the tower base, in the case the wind turbine is considered to be a “building”. In this coordinate system, the forces and moments acting on the tower and the foundation are shown, at least in Germany, in accordance with the guidelines of the Deutsches Institut für Bautechnik (German Institute for Structural Engineering) (DIBt) [2]. The DIBt is attempting to introduce an adaptation to the IEC Standard in the more recent editions of its "Guidelines".

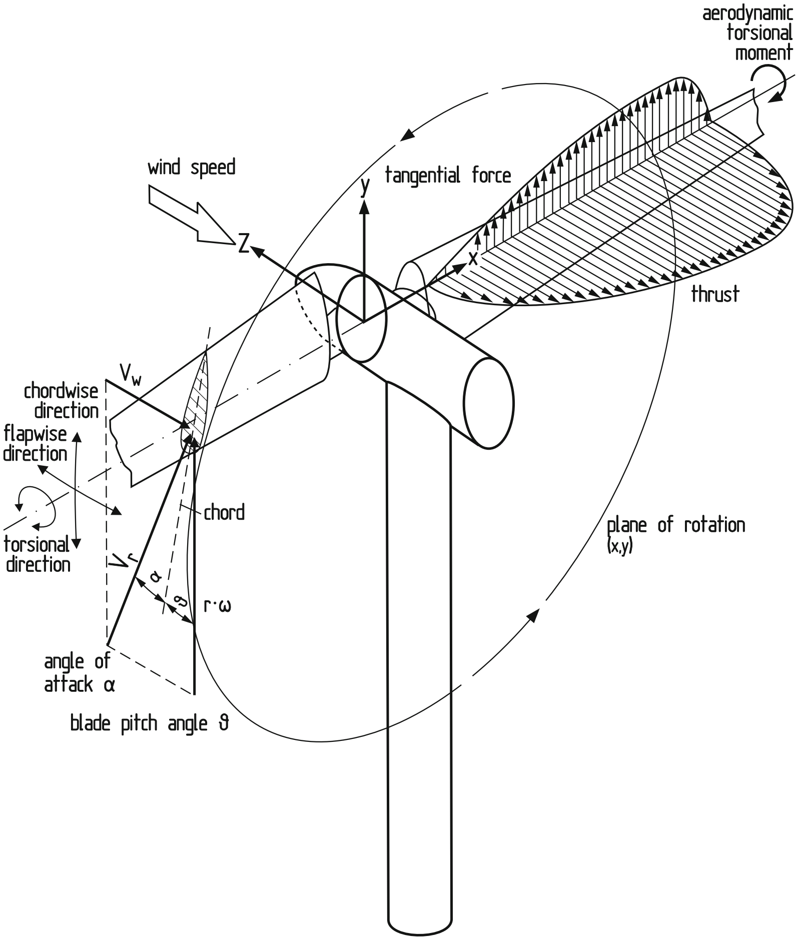

Fig. 6.2. Co-ordinates and technical terms for representing loads and stresses on the rotor

6.3 Sources of Loading

The sources of loading to be taken into account are aerodynamic, gravitational and inertial loads. There are also loads arising from operational actions and different operational states of the wind turbine. In the worst case, many of these sources produce loads simultaneously resulting in cumulative effects.

The complex load spectrum of the rotor and the entire wind turbine becomes comprehensible only when the total loading is mentally resolved into components whose origins are independent of one other. This applies both to the loads due to aerodynamic forces and to those resulting from gravitational and inertial forces. As regards the aerodynamic loads, the load situation is determined by the varying flow conditions acting on the rotor.

6.3.1 Gravity and Inertial Loads

Whereas the aerodynamic loading can only be calculated with difficulty, loads caused by the dead weight of the components and by centrifugal and gyroscopic forces are relatively simple to calculate. The only difficulty is that, at the beginning of the design phase, the masses of the components are not known. As mass can only be calculated as a consequence of the complete load spectrum, including the dead weight, several "iteration loops" are unavoidable when dimensioning the structure. First assumptions as to the weight are best taken from empirical data, prepared statistically from existing turbines.

Gravity loads

Loads resulting from the dead weight of the components must naturally be taken into consideration for all components of the turbine. In a wind turbine, the rotor blade weight is of special significance for the blades themselves, as well as for the "downstream" components.

The rotor blade weight generates alternating tensile and pressure forces along the length of the blade and large alternating bending moments around the chordwise and flapwise axes in the blades over one rotor revolution. The significance of this gravitational loading increases from the blade tip to the root, i.e. in the opposite direction from the influence of the aerodynamic loads. This cyclic loading and particularly the cyclic bending moments around the blade's chord axis, occur with 10^7 to 10^8 cycles during the life of a turbine, assuming a rotor speed of 20 to 50 rpm and a service life of 20 to 30 years. A number of 10^6 load cycles is reached after only approximately 1000 hours operating time. From this number of cycles onward, steel, for example, may only be stressed with its allowable fatigue stress.

Thus, together with wind turbulence, the influence of the gravitational forces becomes the dominant factor for the fatigue strength of the rotor blades. The larger the rotors, the greater these influences will be. As is the case with any other structure, as dimensions grow, it is ultimately the structure's weight which becomes the main problem with respect to strength. For horizontal-axis rotors, the situation is aggravated by the fact that the dead weight causes alternating loads. Proponents of the vertical-axis concept thus rightly point out that for this particular reason, the vertical-axis rotor is more suitable for extreme dimensions, as the alternating loads caused by the dead weight of the rotor blades are avoided.

In the past, some designers of horizontal-axis rotors attempted to compensate for these alternating bending moments by installing lead-lag hinges at the rotor blade roots. These did not, however, prove successful in practice. For one, the complicated mechanisms involved are too expensive and, for another, they are associated with additional problems of dynamics. If the rotor diameter is very large, this undertaking would prove to be pointless, in any case. The better approach, or rather the only possible approach, is to reduce the natural weight of the rotor blades. A lightweight type of construction is almost mandatory for very large rotor blades even if expensive materials such as carbon fibre have to be used.

Centrifugal loads

Centrifugal forces are not very significant in wind rotors, due to their comparatively low rotational speed. This is in contrast to helicopter rotors, where blade strength and dynamic behaviour are determined by the centrifugal forces.

With a special trick, centrifugal forces can even be used to relieve the load on the rotor blades. On some rotors, the rotor blades are inclined downwind out of the plane of rotation, in a slight V-shaped form. This so-called *cone angle* of the rotor blades has the effect that the centrifugal forces, in addition to the tensile forces, create a bending moment distribution along the blade length which counters the bending moments created by the aerodynamic thrust. However, complete compensation can only be achieved for one rotor speed and one wind speed.

If the rotor is subjected to other flow conditions, the effect of the cone angle can be reversed. When the aerodynamic angles of attack are negative, for example with a sudden drop in wind speed, or fast pitching of the blades (rotor emergency stop), the direction of thrust can be reversed for a short time so that the bending moments from the aerodynamic forces and the centrifugal force combine. Whether or not a cone angle of the rotor blade makes sense technically must, therefore, be decided after having taken several aspects into consideration. In more recent turbines there is a tendency to have rotors without cone angle.

Gyroscopic loads

Loads caused by gyroscopic effects occur when the rotating rotor is yawed into the wind. A fast yawing rate leads to large gyroscopic moments, which manifest themselves as pitching moments on the rotor axis. However, as yawing rates are normally low, the practical effects are very slight, or, in other words, the yawing rate must be so slow (approx. 0.5 degrees/sec) that gyroscopic moments do not play a role. It would be uneconomical to have to dimension the structure to the gyroscopic forces (s. Chapt. 10.2). It may occur, that the torsional eigenfrequency of the tower will be excited caused by the yawing motion. This effect has to be considered in the design of the yawing system to avoid additional loading on the tower and on the coupled rotor-tower system.

The attempts to build wind turbines with passive yawing have shown that the gyroscopic forces become a serious problem for these turbines. When wind directions change rapidly, it is unavoidable that the rotor will also be yawed very quickly. Under these conditions, rotor blades, in particular, are subjected to extraordinary bending loads due to the gyroscopic forces involved. Abrupt changes of wind direction are to be expected above all during low wind speeds. This is another reason why passive yawing, which, in any case, can only be implemented on downwind rotors which are no longer being built, is more than problematic (s. Chapt. 10.2).

6.3.2 Uniform and Steady-State Air Flow

Assuming a uniform, steady wind flow is, of course, an idealization which does not exist in the open atmosphere. For practical purposes, this concept is nevertheless useful to calculate the mean load level occurring over a relatively long period of time. If a steady, symmetrical flow entering the area swept by the rotor is assumed, the rotor blades of a horizontal-axis rotor are subjected to steady-state aerodynamic forces. This characteristic distinguishes the horizontal-axis rotor from the rotors with a vertical axis of rotation. Darrieus rotors or similar types are already subject to time-variant loads due to aerodynamic forces under these conditions (Chapt. 5.8). The wind loads on the rotor blades during steady and symmetrical flows are largely determined by the effective wind speed varying from the blade root to the tip. In addition, the geometrical shape of the rotor blades influences the load distribution over the length of the blade. Diagrams 6.3 and 6.4 provide an impression of the aerodynamic load distribution on the rotor blades.

The bending moments on the rotor blades in the chordwise direction are the result of the tangential force distribution, whereas the thrust distribution is responsible for the blade bending moments in the flapwise direction. Owing to the rotor blade twist, in particular, the distribution profile changes distinctly from the start-up wind speed to the shut-down wind speed. The twist is optimized for a nominal wind speed only so that the distribution of aerodynamic loads corresponds approximately to the theoretical optimum only for this windspeed. At other wind speeds, especially higher ones, the flow separates in the blade sections near the hub. This causes the distribution of the aerodynamic loads to change considerably.

Integrating load distributions over the length of the rotor blade yields the overall rotor loads and moments. The tangential loading provides the rotor torque, and the thrust load distribution provides the total rotor thrust. These two parameters essentially determine the static load level for the entire turbine. In rotors with blade pitch control, rotor torque and rotor thrust increase continuously up to the point where the control system limits the power to the rated power (Fig. 6.5). Rotor thrust is greatest at the rated power point, then drops off again.

In the case of rotors not incorporating pitch control, where power capture is restricted merely by aerodynamic stall, rotor thrust continues to increase, or remains at an approximately constant level, after having reached rated power. For this reason, among several others, turbines without pitch control are subjected to higher steady-state loads (Chapt. 5.3.3).

The previous examination of the loads on rotor blades only relates to the distribution of loads in the direction along the blade. This two-dimensional load picture in reality masks a "mountain range" of loads which also extends in the direction of the blade chord. Information about load distribution over the blade chord is usually of minor significance but is, nevertheless, necessary for dealing with some problems concerning torsional stiffness of the blade. Furthermore, this load distribution must be taken into consideration when dimensioning the skin and ribs of the rotor blade, at least when dealing with large rotor blades with a correspondingly deep chord.

The chord-wise load distribution is usually derived from pressure distribution measurements, carried out on model airfoils in the wind tunnel. Airfoil catalogues contain information on these pressure distributions. They are characteristic of each airfoil and vary with the aerodynamic angle of attack (Fig. 6.6). Moreover, like the shape of the airfoil lift and drag characteristics, they are affected by the Reynolds number. Hence, applying them to the airfoil cross-sections of the original rotor blade must be done with some care.

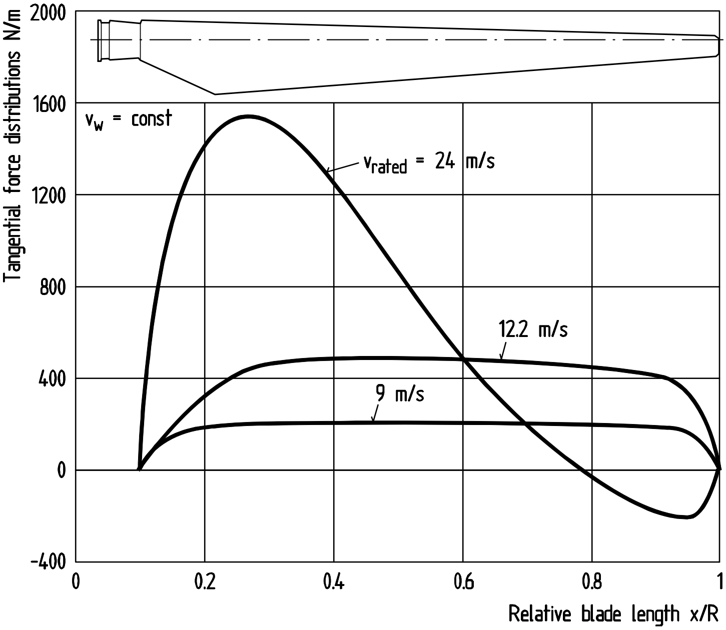

Fig. 6.3. Tangential load distribution over the blade length of the experimental WKA-60 wind turbine

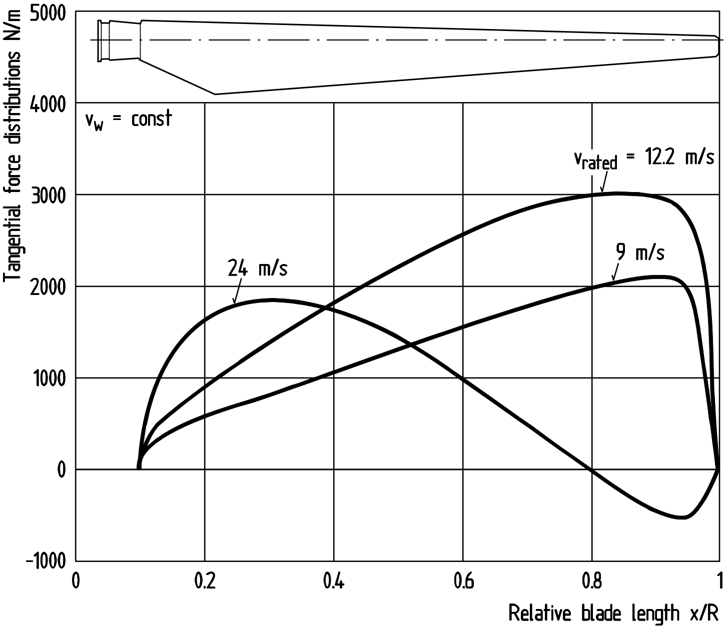

Fig. 6.4. Thrust load distribution over the blade length of the WKA-60

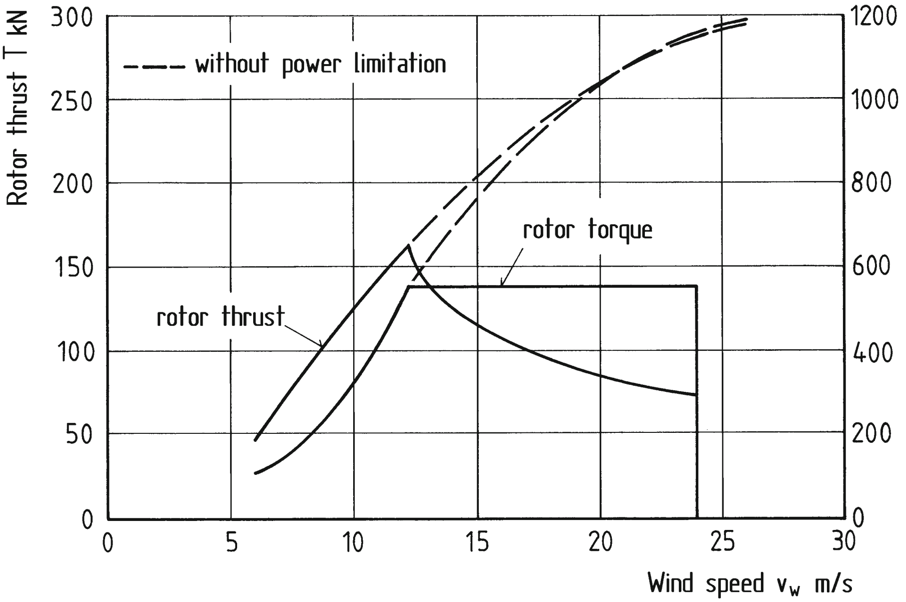

Fig. 6.5. Torque and rotor thrust with a steady air flow on the WKA-60

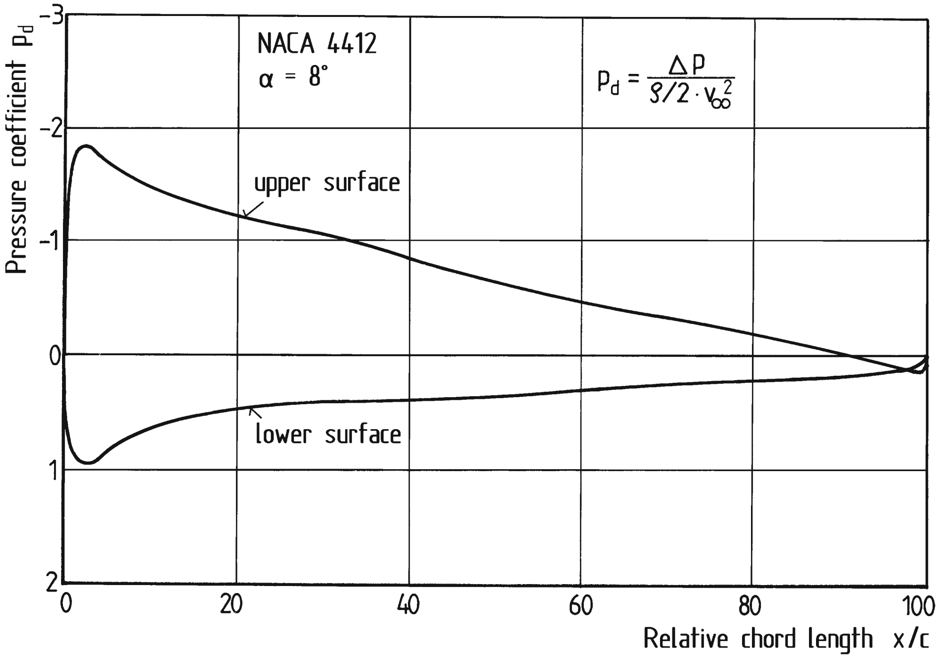

Fig. 6.6. Aerodynamic pressure distribution for the NACA 4412 airfoil [3]

6.3.3 Vertical Wind Shear and Cross Winds

The wind flow produces unsteady, cyclically varying loads as soon as it strikes the rotor asymmetrically. One unavoidable asymmetry of the oncoming wind flow is caused by the increase in wind speed with height. During each revolution, the rotor blades are subjected to higher wind speeds in the upper rotational sector and are thus subjected to higher loads than in the sector nearer the ground. A similar asymmetry of flow at the rotor is caused by the largely unavoidable crosswinds which occur with fast changes in wind direction.

The vertical wind shear and crosswinds on the rotor lead to a cyclically increasing and decreasing aerodynamic load distribution over the rotor blades. Compared to the basic loading with a steady, symmetrical wind, there are considerable variations in load (Fig. 6.7). The linearly asymmetrical wind stream assumed here in this example qualitatively stands for the vertical wind speed profile or also for an asymmetrical wind flow due to a change in wind direction.

The changing aerodynamic loading on the rotor blades during one rotor revolution, of course, also means varying total rotor loads and hence varying loads for the remaining parts of the turbine. The cyclically changing pitching and yawing moments, in particular, represent considerable fatigue loads for the mechanical components of the yaw drive. This applies especially to hingeless two-bladed rotors. For this reason, large wind turbines with two-bladed rotors are usually built with a *teetering hub,* which more or less compensates for these changing loads.

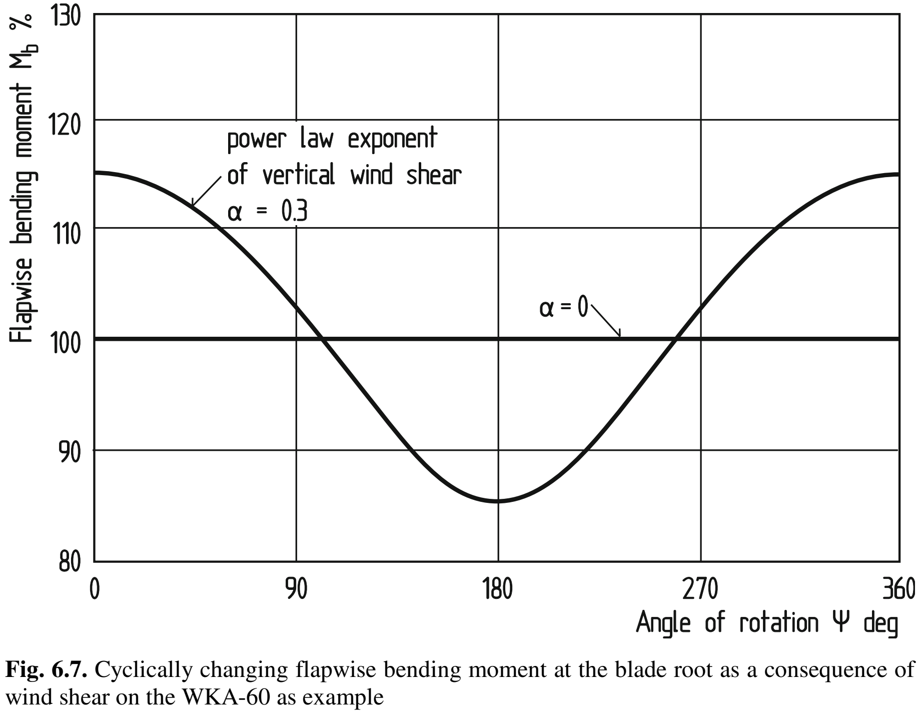

Fig. 6.7. Cyclically changing flapwise bending moment at the blade root as a consequence of the wind shear on the WKA-60 as example

6.3.4 Cross Wind on the Rotor

A similar asymmetry of rotor cross wind as that due to the increase in wind speed with height is produced by the cross wind on the rotor as a consequence of rapid changes in the wind direction. The relatively inert yaw drive can follow these only with a considerable time delay so that the incident airflow exhibits a yaw angle with respect to the rotor axis at times. In addition, asymmetric inflow conditions for the rotor can be caused by diverted wind streams in the case of topographically complex terrain or also due to the rotor design in the case of an inclined rotor axis. This is another reason for keeping the rotor axis inclination as small as possible although it is required with very flexible rotor blades in order to guarantee that sufficient free space is maintained between the blade tips and the tower when maximum deflection occurs.

The mathematical treatment of the rotor in a cross wind with respect to the aerodynamic forces is not simple. Some useful approaches in this respect are provided by the blade element theory but these remain valid only up to certain yaw angles. Some possibilities which are better in part are given with the vortex model of the rotor [4]. Figure 6.8 shows the result of a measurement on an experimental installation of the Dutch ECN Institute. The authors point out that the agreement with the mathematical results is still acceptable at a yaw angle of up to 20^0 whilst the measured effect is clearly underestimated by the theory at an angle of 30^0.

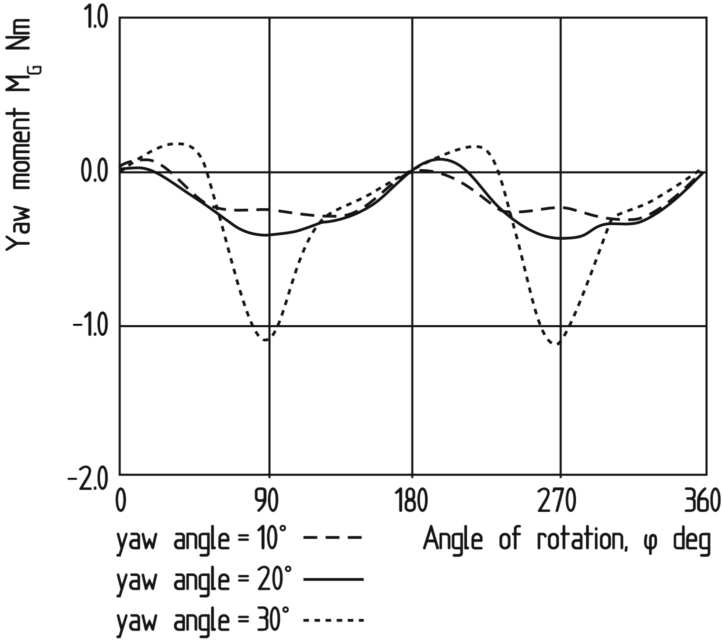

Fig. 6.8. Measured yaw moment of the rotor at various crosswind angles on a Dutch 2-bladed test rotor in the wind tunnel [5]

6.3.5 Tower Interference

The rotor of a horizontal-axis wind turbine necessarily rotates in close proximity to the tower. The clearance between the rotor rotational plane and the tower is generally kept as small as possible in order to limit the length of the nacelle. A nacelle which protrudes very far causes the rotor forces to act with great leverage with respect to the tower axis. In any case, however, the distance between rotor and tower is so small that the aerodynamic flow around the tower influences the rotor.

The influence of the aerodynamic flow around the tower on the rotor is at a minimum when the rotor is mounted in the traditional position upwind of the tower. The upwind rotor is affected merely by a retardation of the flow in front of the tower, the so-called “bow wave” or *tower dam* effect. This tower dam effect was still a considerable factor with the old-style windmills and their mill houses, but with today's slender towers it is only slight. Its effect is still perceptible, but the practical effects on rotor loading are slight as long as a minimum clearance between rotor blade and tower of approximately one tower diameter is maintained (Fig. 6.9). However, the tower dam is a possible hazard with respect to the excitation of tower vibration if the rotor speed remains within the range of the natural bending frequency of the tower for any length of time (Chapt. 11.4).

A completely different problem arises when the rotor is mounted on the down-wind side of the tower. This type of design used to be considered to be advantageous in connection with the slender towers in the large first-generation wind turbines.

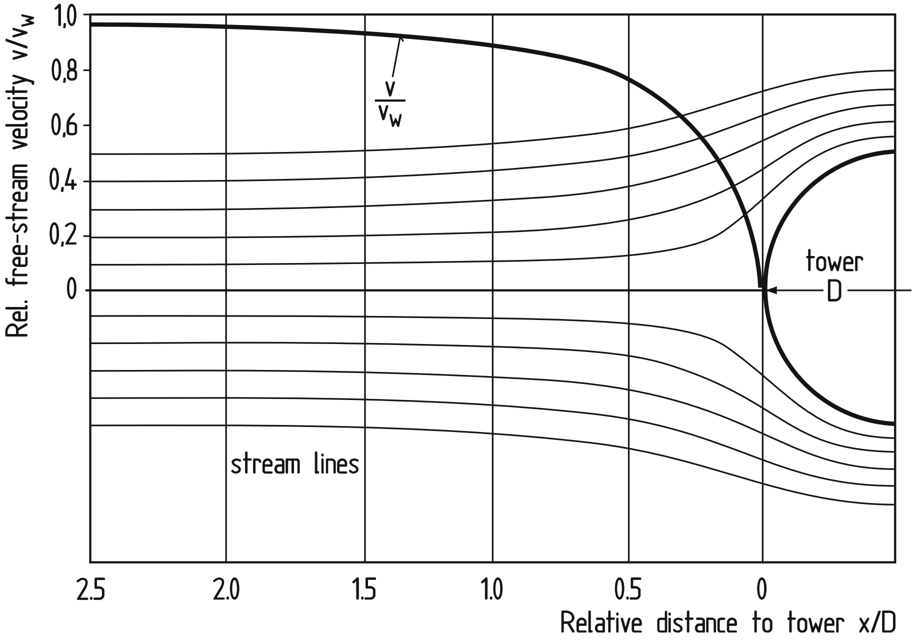

Fig. 6.9. Flow field due to the tower dam ahead of a cylindrical tower with diameter D (potential flow theory)

A reduction in flow velocity on the down-wind side of the tower is still perceptible even at a relatively large distance. The rotor blades must pass through this wind-sheltered area with each revolution. This *tower shadow* effect represents a serious problem for the wind turbine in several respects it must be discussed more extensively.

The aerodynamic influence of the tower has to be considered even in the case of an upwind rotor. As almost all towers of modem turbines have a circular cross-section, only the flow around a circular cylinder has to be considered. The internal friction of the flowing medium and the surface friction (boundary layer) of the body encountered cause an area of detached flow behind the body, the so-called *wake* area (Chapt. 5.4). The wake in the flow behind a circular cylinder consists of a more or less extensive area of increased turbulence with a considerably decreased mean flow velocity. Another typical characteristic of the wake behind a body with a circular cross-section are the alternating vortices on both sides, occurring with a defined frequency *(Karman vortices).* Depending on the Reynolds number of the flow, which is referred to the cylinder diameter, three characteristic regions can be observed (Figs. 6.10 and 6.11).

Subcritical region

When the Reynolds number is below approximately 3 to 4×10^5, i.e., at a slow flow velocity, the boundary layer remains laminar. Flow separation takes place ahead of the widest point of the cylinder cross-section. The flow wake is relatively wide and distinct Karman vortices occur periodically. Under these conditions, the air drag coefficient of the circular cylinder is relatively high and equals approximately 1.0.

Supercritical region

At a certain flow velocity, characterised by the so-called "critical Reynolds number", the boundary-layer flow at the cylinder surface shifts from a laminar to a turbulent condition. This effect influences the shape of the wake considerably. The high-energy, turbulent boundary layer causes the flow around the body to persist, so that the flow wake is narrowed. The periodic Karman vortices disappear almost completely. The drag coefficient is drastically reduced to values of between 0.25 and 0.35. As it is a boundary-layer effect, the point of change is influenced by the surface roughness of the object.

Transcritical region

Above the critical Reynolds number there follows a "transitional region" where the flow wake starts to become wider again. In the transcritical region, the drag coefficient rises to values of approximately 0.5. The Karman vortices again occur periodically, but somewhat more weakly.

A brief estimate of the flow around a tower of a large wind turbine shows that with tower diameters of several meters and wind speeds of between 5 and 25 m/s, the Reynolds numbers are so high that a turbulent flow can always be expected.

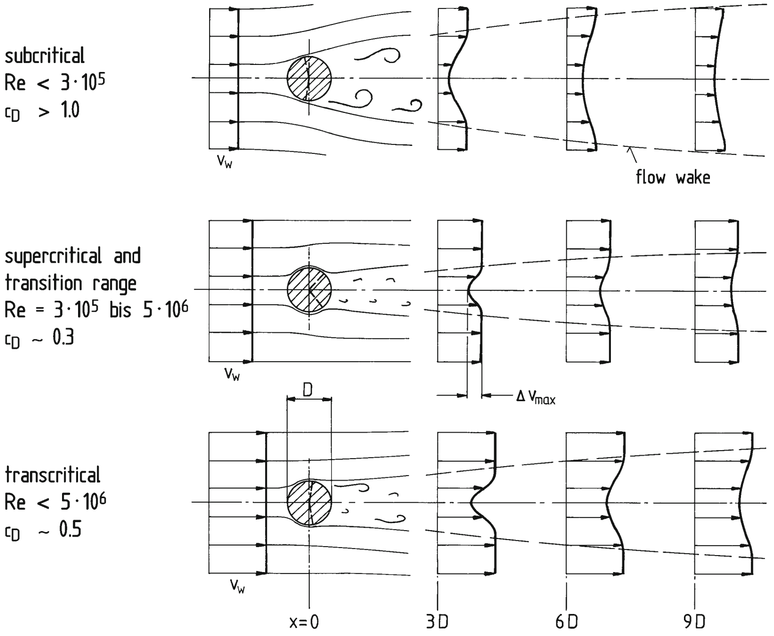

Fig. 6.10. Flow around a circular cylinder in dependence on the Reynolds number

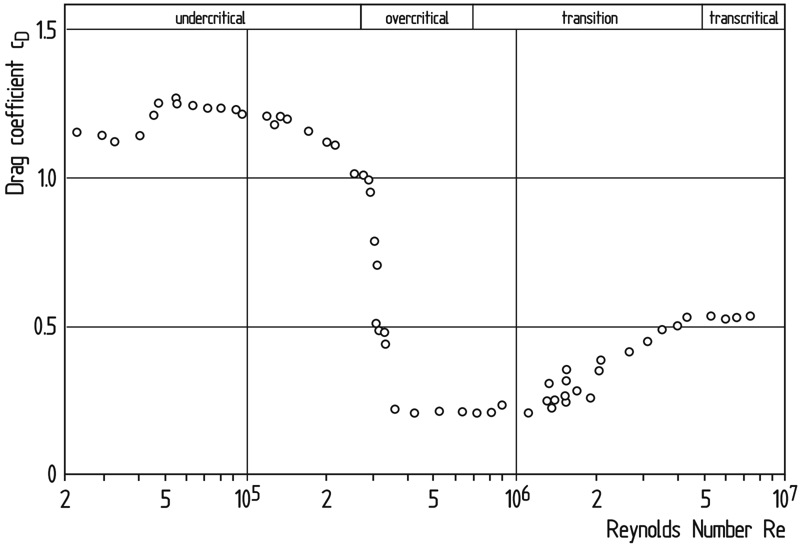

Fig. 6.11. Air drag coefficient of a circular cylinder in dependence on the Reynolds number [6]

In this region, the maximum wind speed reduction in the flow wake can be estimated by the following formula:

$$\frac{\Delta v_{max}}{\bar{v}_W} = 1 - \sqrt{1 - c_D}$$

How does the tower shadow affect the aerodynamics of the rotor? First of all, the reduced flow velocity to the rotor blades as they pass through the tower wake is an important factor. Reduced wind speed goes hand in hand with a change in the effective aerodynamic angle of attack. Both lead to a sudden decrease in the lift of the rotor blade. It affects both the aerodynamic loading and the torque generated.

This process is of very short duration, corresponding to the rotor speed, and represents an impulse-like disturbance at the rotor blade. From the aerodynamic point of view, this means that transient aerodynamic effects can play a role which means, for example, that the temporal gradient of the change in the angle of attack can have a significant influence on aerodynamic forces and moments. While the treatment of transient aerodynamic problems is difficult, it can, however, become necessary when attempting a theoretical treatment of the tower shadow problems of a down-wind rotor.

On the other hand, the disturbance due to the tower wake continues for long enough for elastic yielding of the rotor blades to have a damping effect. Thus, the tower wake is also a problem of aeroelastics, i.e. the dynamic response of the rotor blades. Figures 6.11 and 6.12 show two examples of the effects of the tower wake on a down-wind rotor.

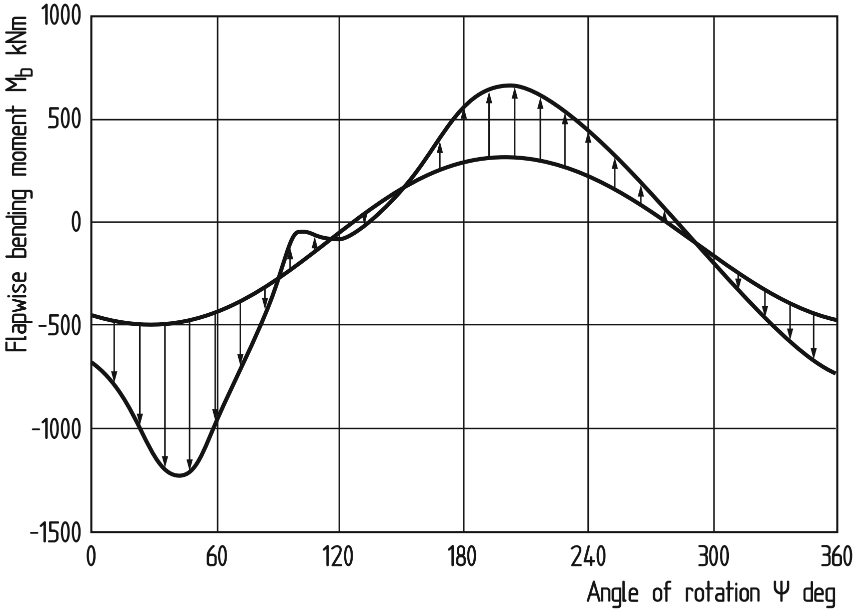

Fig. 6.12. Calculated increase in the flapwise bending moment at the blade root due to the tower shadow, using Growian as an example

In the case of a downwind rotor the tower shadow contributes to a considerable extent to the load spectrum. The flapwise bending moment is an important parameter for rotor blade dimensioning. The influence of the tower shadow is considerable, especially considering the high number of load cycles of 10^7 to 10^8 during the life of the turbine (Fig. 6.12). The tower shadow effect thus becomes a factor which cannot be ignored with regard to the fatigue life of the rotor blades.

The electric power output of down-wind rotors is a clear indicator of the influence of tower shadow interference. In extreme cases, power losses of up to 30 or 40 % below the average output were measured (Fig. 6.13). At the usual rotor speeds, the frequency of tower shadow interference falls within the range of some of the critical natural frequencies of the turbine, in particular that of the drive train (Chapt. 11.2.4).

Last but not least, the influence of the tower shadow on the noise generated by the wind turbine must also be pointed out (Chapt. 15.2.2). This effect turned out to be of such importance that it caused the virtually complete disappearance of downwind rotors among today's wind turbines.

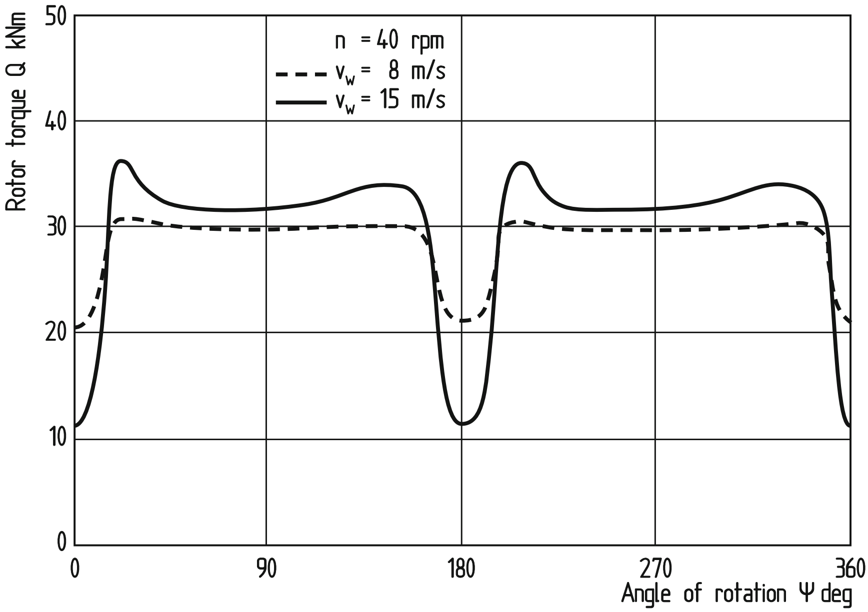

Fig. 6.13. Influence of tower shadow on the rotor torque at the example of the experimental MOD-0 wind turbine [7]

6.3.6 Wind Turbulence and Gusts

While power output and energy yield of a wind turbine are determined by the long-term variations of the mean wind speed, the non-cyclic fluctuating loads on the wind turbine are determined by the short-term fluctuations of the wind speed, the wind turbulence and the gusts. The ever-present wind turbulence contributes considerably to material fatigue, particularly of the rotor blades. Extreme wind speeds, though far more rare, must also be taken into consideration when designing for fatigue strength. Moreover, they can increase loads up to the point of fracture. The most serious problems as far as loading is concerned are presented by the stochastic fluctuations of the wind. There is a number of different "turbulence models" which can be traced back to two fundamental approaches (see Chapt. 13).

Spectral model of turbulence

The continuous nature of the wind speed fluctuations is reproduced best by means of a statistical approach in the form of a turbulence spectrum. The spectral representation of the wind is also used in general meteorology where the most varied turbulence spectra have been developed. Common turbulence spectra have been produced by Davenport, Kaimal or von Karman and can be found in the relevant literature (see Chapt. 13.3.4).

In the load calculations it is generally assumed that the turbulence is a one-dimensional fluctuation of wind speed in the longitudinal direction. In reality, wind speed fluctuations naturally also have lateral components. Mathematical treatment of a two-dimensional turbulence model is very difficult, however, and generally not necessary when dealing with wind turbines. More important, as far as loading on the wind rotor is concerned, is the spatial distribution of longitudinal turbulence over the rotor-swept area.

Gust model

While the spectral model of turbulence is of a statistical nature, a deterministic approach can also be used. The basic idea is to define discrete idealised gust shapes, represented by increasing and decreasing wind speed over time. These gusts are then assumed to be discrete isolated events for the calculation of loads. It is obvious that in the process, the continuous nature of the turbulence is lost. The response of the structure shows only the reaction to an isolated gust, without taking into consideration the situation before and immediately after the event. For this reason, the gust model is unsuitable for calculating fatigue strength. Gust models were used only in the initial phase of wind energy technology, in which, provided with a probability of occurrence, a load spectrum was assembled from various forms of gusts and used as input for the fatigue calculation. Present-day calculation methods are based without exception on the spectral model of turbulence

The significance of these *discrete gusts* for load calculation primarily lies in the determination of extreme loads. For this purpose, the characteristic properties of the gusts must be known. Meteorological research has not given much attention to this special problem so far, so that no adequate data on gust factors, rise and fall times, spatial extent and similar parameters are available. Attempts to compile data usable for wind energy technology today were carried out, in particular, by Frost [8]. From such data, idealised gust shapes have been derived for calculating loads on wind turbines (Fig. 6.14).

Frost specified gust factors as a function of gust duration (Fig. 6.15). They also depend on the level of the mean wind speed. The higher this is, the smaller are the gust factors to be expected. The frequency of occurrence is also to be seen in connection with the mean wind speed and the gust factor (Fig. 6.16).

Figure 6.17 shows the effect of wind turbulence on the specific dynamic load situation of a wind turbine. Bending deflection in the rotor blades was initially calculated taking into account only the influence of the cyclic disturbances in the flow caused by wind shear, tower influence and similar parameters, but ignoring turbulence. Including the turbulence spectrum, the deflection values are almost doubled.

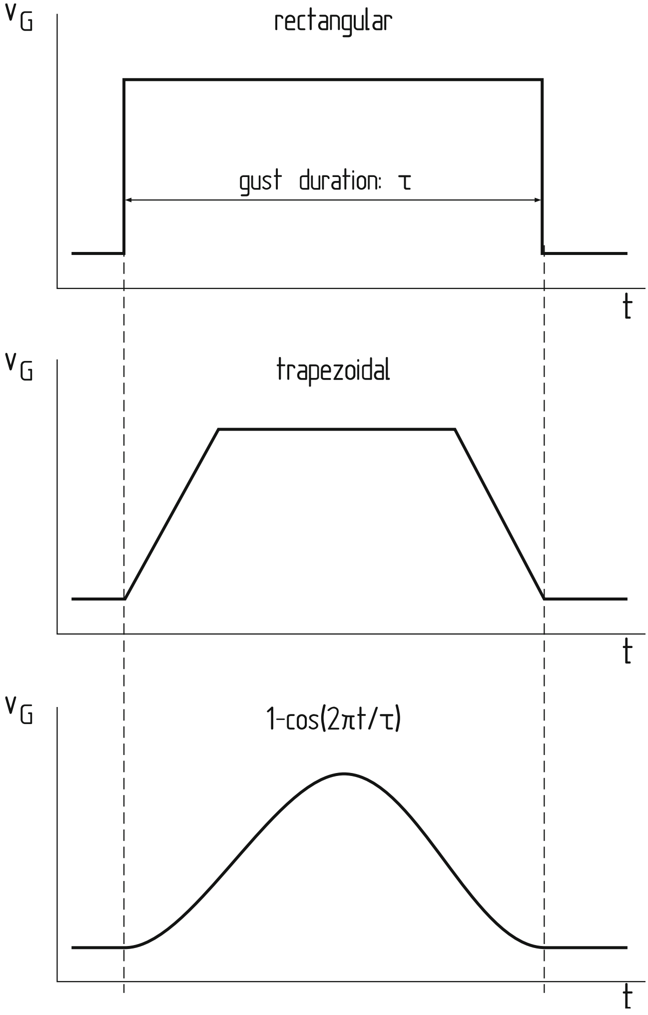

Fig. 6.14. Idealised gust shapes [8]

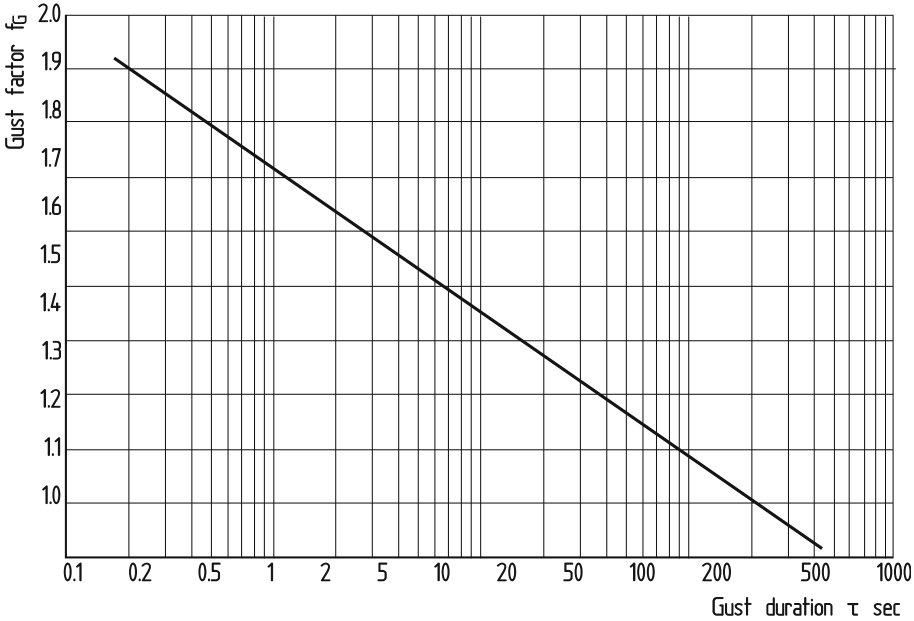

Fig. 6.15. Gust factors in dependence on gust duration [8]

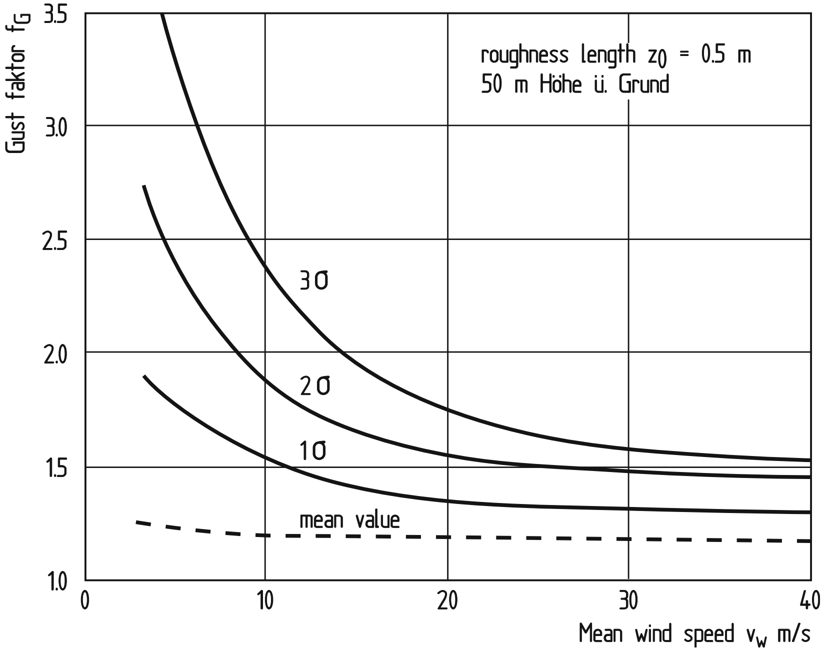

Fig. 6.16. Gust factors in dependence on the mean wind speed and occurrence probability [8]

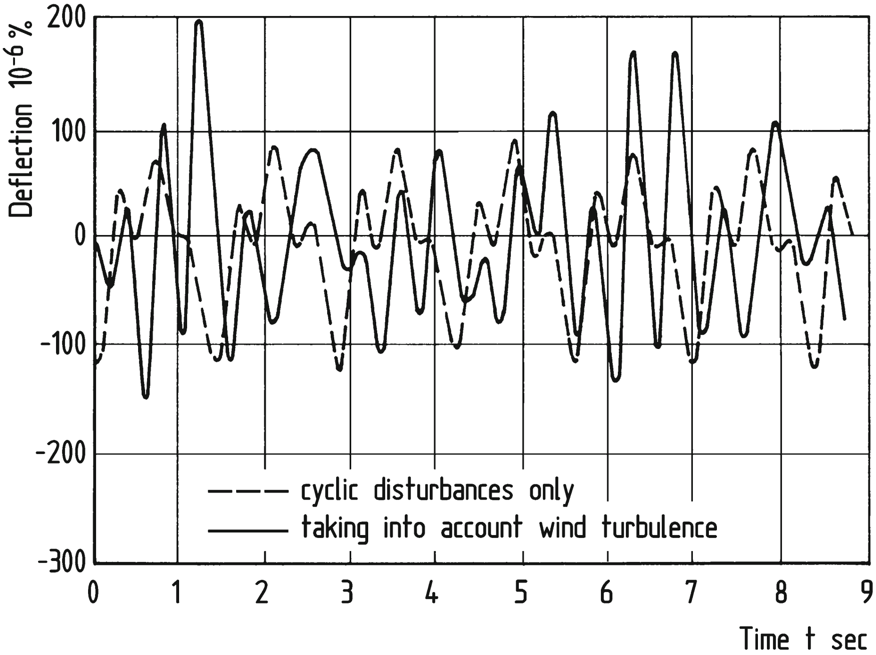

Fig. 6.17. Rotor blade bending deflection in flapwise direction, at the HWP-300 wind turbine [9]

6.4 Design Load Assumptions

If the reasons for loads are known, the task is to recognise the conditions during which the wind turbine is subjected to the essential loads. These conditions and the loads occurring in them are recorded in the form of so-called *load assumptions* in which both the external conditions for the causes of the loading, for example the wind speeds and the turbulence, and the corresponding parameters of the state of the turbine such as rotor speed or rotor blade pitch angle are established.

It is not apparent from the outset in which load case the dimensioning loading of different types such as fracture, fatigue or failure of stability will occur. The definition and systematic arrangement of the load cases must, therefore, be comprehensive enough to include all operating conditions and additionally also other critical states in the life cycle of the system which can be expected with a certain probability. This opens up another problem of the system of load cases: the probability of occurrence. If one were to define as a load case all conceivable combinations of states and external conditions, i.e. of the hurricane of the century with simultaneously occurring especially bad operating conditions, the design process would be carried ad absurdum. The load cases on which the design is based, and thus, naturally, also the failure of the system, are turned into a question of statistically based probabilities. Naturally, this applies not only to wind turbines but to all technical systems and structures.

A further problem consists in that the specification of load cases and the loads to be stipulated are always associated with a certain idealisation and simplification of a real state. The loads determined by calculations in the defined load cases are therefore *load assumptions* which deviate from the real loads to a certain degree. However, this deviation from reality must always be to "the safe side". In other words, the load assumptions used for the design must always be somewhat higher than the loads actually to be expected in operation.

According to their intended purpose, load assumptions should have a general validity as far as possible, so that they form a generally accepted basis for the design of a system, claims which form the basis for the existence of the "Norms" and "Standards" described in the next chapter. On the other hand, the technical concept of the turbine influences the nature and extent of the loading to a certain degree so that certain load cases occur only with certain technical concepts. A mixture of general validity and individual significance is thus largely unavoidable.

It should also be pointed out that, as a rule, the terms "load cases" and "load assumptions" are not clearly delimited with respect to one another. Strictly speaking, the term "load case" designates the situation in which loads occur. This situation is defined by the external conditions, on the one hand, and, on the other hand by the machine status (see Chapt. 6.5). The load assumptions per se are the idealised loads to be stipulated in the load cases. However, the term load assumptions is often also used as the generic term for the totality of design loads which are then classified as individual load cases.

6.4.1 International and National Design Standards

First attempts at a systematic definition of load assumptions and load cases for modern wind turbines had been undertaken in the eighties in connection with the development of the large experimental Growian and WKA-60 wind turbines [10]. The standards were initially developed on a national basis but information was exchanged especially under the auspices of the International Energy Agency (IEA) as early as the beginning of the eighties [11]. Germanischer Lloyd used this as a basis for building up their set of regulations which represents an important basis for many wind turbine developments until the present day.

At the same time, similar standards were also produced in the US, in Denmark and in Sweden. In 1988, the International Electrotechnical Commission (IEC) took over this task on an international basis.. Today the national rules and regulations have largely been replaced by the IEC standards, although the national standards are still in existence since the European standards still do not have unrestricted legal force. Against this background, a "sideways glance" into the national building regulations is sometimes still necessary.

Up to now the following regulations have been published by the IEC:

IEC 61400-1	Safety Requirements
IEC 61400-2	Safety Requirements of Small Wind Turbines
IEC 61400-3	Design Requirements for Offshore Wind Turbines
IEC 61400-11	Acoustic Noise Measurement Techniques

IEC 61400-12	Wind Turbine Performance Testing
IEC 61400-121	Power Performance Measurements of Grid Connected Wind Turbines
IEC 61400-13	Measurement of Mechanical Loads
IEC 61400-21	Measurement and Assessment of Power Quality Characteristics of Grid Connected Wind Turbines
IEC 61400-23	Full Scale Structural Testing of Rotor Blades
IEC 61400-24	Lightning Protection
IEC 61400-25	Communication Standard of Control and Monitoring of Wind Power Plants

The decisive document with regard to the load assumptions is the IEC 61400-1 standard "Safety Requirements". The statements contained in the following chapters are, therefore, an excerpt from IEC 61400-1.

On the basis of the IEC standards numerous so-called “certification organizations” offer an independent certification service for wind turbines. They also consider to a certain extent inhouse or national standards for some aspects of the design or for the load calculations. The most important classification organizations, which grant certifications for wind turbines are:

Germanischer Lloyd

The guidelines of the Germanischer Lloyd (GL) are of particular importance in Germany but some other European countries are also working with these guidelines or are using the certification by the GL. The rules are more detailed than those of the IEC in some aspects and also comprise rules for the mathematical methods to be used. From the point of view of content, there are some differences to be noted. For example, the intensity of turbulence to be assumed, which forms the basis of the load cases, is different. Whilst the IEC is assuming turbulence intensities of 15-18 %, the GL guidelines require 20 % overall. However, these and some other small deviations are about to be corrected.

Det Norske Veritas

Next to the Germanischer Lloyd, Det Norske Veritas (DNV) is the second international classification company which has its origin in shipbuilding. The DNV has also issued "Guidelines for the Design of Wind Turbines". In principle, the same applies as for the GL guidelines, i.e. there are still some deviations from IEC 61400-1 in detail.

Besides the IEC-standards some national standards are still in force, particularly the standards in the Netherlands, Denmark and Germany. They play a role in the national building permissions. Some regulations of the national standards are not included in the IEC standards.

Dutch NVN Guideline 1400-0

In the Netherlands, there is the NVN guideline for the construction of wind turbines. It is largely related to IEC 61400-1. There are only a few deviations in the safety factors to be applied.

Danish Standard DS 472

In Denmark, the national body of rules "Loads and Safety of Wind Turbine Construction" (DS 472) applies. This, too, largely matches IEC 61400-1. There are still differences in the definition of wind speed classes (see Chapt. 6.4.2). There are also special, simplified regulations for the construction of stall-controlled turbines with a rotor diameter of up to 25 m.

German DIBt Guidelines

In Germany, wind turbines are legally graded as "buildings". The technical type approval and the planning permission are therefore under the jurisdiction of the competent building authorities. These use the certification companies, e.g. the GL, as expert assessors for the "technical part" of the building. This procedure, which appears to be somewhat whimsical, has led to the "Deutsches Institut für Bautechnik (German Institute for Structural Engineering) (DIBt)" issuing their own guidelines for the construction of wind turbine installations. Although these relate primarily to the so-called "Proof of Stability for Tower and Foundation", they contain many specifications which relate to the wind turbine as a whole. By now, these relate largely to the IEC Standard but there are still differences, primarily the so-called "wind zones" which are not identical with the wind speed values in the "wind turbine classes" according to IEC (see Chapt. 6.4.2).

Certification business

The "certification" of wind turbines has become an extensive branch of the trade which requires some relevant critical remarks with which not everyone may agree. The independent verification, i.e. testing of the structure with respect to safety, is quite indisputably in the public's interest and is therefore a "must". Checking the performance characteristic by manufacturer-independent neutral institutes or expert assessors also makes sense. In Germany, this check is not a subject for the type approval. The purchaser should be aware of this fact and in his own interest request to see the certificates for the performance characteristic.

The newly developed fields of wind energy utilization such as, for example, the offshore siting of wind turbines, make completely new demands on the design and the technical equipment. The development of the design standards and the certification must keep up with these developments which makes it unavoidable that the latest and more extensive sets of rules must always be available.

On the other hand, the certification activities are increasingly spreading to almost all aspects of wind energy utilisation, following a trend to have every characteristic of a

product or even of an associated action like the investment in a wind farm authenticated and certified by independent experts. Against this background, extensive test procedures were developed for wind turbines which are reflected in the most varied test certificates. From the environmental conditions through the load assumptions, from the construction to the surveying of wind turbine installations, all these fields are the subject of certifications. Without any claim for completeness,
these are:

- Production methods,
- Quality assurance,
- Test procedures,
- Transportation,
- Erection and assembly,
- Commissioning,
- Maintenance regulations,
- Operational sequences,
- Quality of power output,
- Electrical characteristics and grid compatibility et al.

Most of the organisations offering certifications are profit-oriented commercial undertakings. For this reason, they will attempt to extend their services to all possible areas. However, in many areas it is more than doubtful whether a "certificate", for example for "production" or for "transportation", has any objective use. Neither is the situation improved by the fact that the organisations have for some years been advertising so-called "accreditations" which, in turn, are issued by private commercial organisations. This practice, too, and the standards of the authorities which extend over ever more new fields, serve the general need of the consumers for ever more safeguards and less personal responsibility.

As ever, the decisive criterion for the quality of a product is the technical competence and financial capacity of its manufacturer. It is only the manufacturer who really bears responsibility for his product through his warranty. If something goes wrong, the financial consequences will hit the manufacturer and his customer, never the certification organisations. Certificates, however attractive-sounding, are therefore no substitute for trust in the manufacturers and their product.

6.4.2 IEC Classes of Wind Turbines and German Wind Zones

The structural dimensioning of a wind turbine is determined to a considerable extent by the wind conditions at the intended site. The demands on structural strength are much lower on sites with relatively low wind speeds and little turbulence than on sites with high average wind speeds and corresponding air turbulence. The turbulence can also be increased by particular forms of terrain (see Chapt. 13.4). For this reason, the load assumptions are adapted to the different wind conditions. It would not make any economic sense to design the structural strength sweepingly for the highest wind speeds and on-site conditions occurring.

IEC 64100-1 defines four different classes of wind conditions called "Wind Turbine Generator System Classes" (WTGS Classes). The wind conditions are defined by the extreme wind speeds to be assumed and the average wind speed at the site, and by the turbulence intensity. The extreme wind speeds are aimed at ensuring that adequate breaking strength and stability is provided whilst the average wind speed is of importance for the service strength, i.e. the fatigue strength, of the material. In this context, a design life of at least twenty years must be used as a basis.

A so-called *reference wind velocity* is used for identifying the different classes. This is the maximum wind speed which, seen statistically, is exceeded only once in 50 years and is measured as a ten-minute mean value. The short-term extreme wind speeds within a 3-second period, i.e. the maximum gusts to be expected, are derived from this value. The wind turbulence is assumed to be characterised in two categories A and B. The standard deviation of the longitudinal wind velocity change in the 10-minute mean values is specified by the parameter α (Table 6.18). Apart from these four classes, there is also a special class S for special site conditions. The values to be assumed in this class must be agreed individually with the licencing authorities. In addition, the Germanische Lloyd has defined a new "Off-shore" class which has been adopted by the IEC [12].

Table 6.18. WTGS Classes to IEC 64100-1

WTGS class	I	II	III	IV	
V_{ref} (m/s)	50	42.5	37.5	30	50-year annual wind speed (10 min., average at hub height)
V_{ave} (m/s)	10	8.5	7.5	6	1-year annual wind speed (10 min., average at hub height)
A I_{15} (-) α (-)	0.18 2	0.18 2	0.18 2	0.18 2	Characteristic turbulence, high at V_W = 15 m/s
B I_{15} (-) α (-)	0.16 3	0.16 3	0.16 3	0.16 3	Characteristic turbulence, low at V_W = 15 m/s

It should be pointed out that in conjunction with the IEC Standard, the indices defined there are used for identifying the parameters. Otherwise, the older indices still in common use in Germany and used in the other chapters would have to be continuously compared with the designations of the IEC Standard and confusion is preprogrammed.

There is another special feature to be noted in Germany which, although it is of no importance internationally, will still play a role in Germany for the foreseeable future. The Deutsches Institut für Bautechnik has also introduced a classification in its Guidelines for Wind Turbines which contain the so-called *Proof of Safety* for tower and foundation [2]. The wind conditions are graded into so-called *Wind Zones*. The proof of stability is, therefore, checked in accordance with the defined wind zones as part of the building permit procedure. On the other hand, the manufacturers of wind turbines almost exclusively use the IEC classes as a basis for the technical engineering part. For this reason, there is frequently a problem of compatibility of the DIBt wind zones with the wind turbine classes according to IEC.

The DIBt defines the following wind zones and specifies the reference wind speed at 10 m height for these (not at hub height as with the IEC):

- Wind Zone I:	Weak-wind regions (24.3 m/s)
- Wind Zone II:	Normal German inland site (27.6 m/s)
- Wind Zone III:	Typical coastal site (32.0 m/s)
- Wind Zone IV:	North Frisian islands (36.8 m/s)

The IEC class 1 forming the basis for the design of wind turbines corresponds approximately to Wind Zone IV, IEC Class 2 corresponds to Wind Zone III and IEC Class 3 can be equated with Wind Zone II. The precise differences are deliberately not taken into consideration here since it is hoped that they will soon be a thing of the past in the course of the on-going harmonisation of standards in Europe as well as internationally.

6.4.3 Normal Wind Conditions

The so-called "normal wind conditions" reflect the wind conditions occurring "frequently", i.e. frequently in the course of a year, during the operation of a wind turbine. They are characterized by:

Mean annual wind speed

The mean annual wind speed at rotor hub height, measured as a 10-minute mean value, is the most important parameter for characterizing the wind conditions. With respect to the fatigue strength, it is not only the fluctuation of the instantaneous wind speed about the annual mean value which plays a role but also the longer-term variations of the mean wind speed. Although their associated frequency of load cycles is lower by several orders of magnitude, they still have a certain influence on the fatigue strength. Seen from the point of view of the total load spectrum, they represent transitions from one wind speed class to another. They can be interpreted as long-wave, periodic oscillations with large amplitudes.

Wind speed frequency distributions

The wind speed frequency distribution is assumed to be a Rayleigh distribution (Weibull distribution with a form factor of $k = 2$).

Vertical wind shear

The vertical wind shear indicates the average change in the mean wind speed with height. It is accounted for by Hellmann's power law with the exponent used being $\alpha = 0.20$. The vertical profile of the wind speed is of considerable significance, for example, for the flapwise bending moment if the rotor blades. The high numbers of load cycles are the result of the speed of rotation of the rotor and are correspondingly high with a stipulated rotor design life of 20 years.

Wind turbulence

Apart from the cyclic loads resulting from the dead weight of the components and the asymmetrical flows on the rotor, wind turbulence is the second decisive factor for the fatigue strength. According to IEC 64100-1 the "normal turbulence" of the wind is described by the standard deviation:

$$\sigma_1 = I_{15} \cdot (15\,m/s + \alpha\, v_{hub}\,(\alpha + 1))$$

The parameters depending on the wind turbine class are contained in Table 6.18.

6.4.4 Extreme Wind Conditions

To determine the maximum loads on the wind turbine, "extreme wind conditions" must be stipulated. These comprise short-time extreme wind speeds and also the loads resulting from extreme changes in the wind direction and the vertical shear in the wind speed, and certain combinations of these influences. The continual nature of the turbulence is covered with the statistical approach to turbulence during normal wind conditions so that the extreme events can be assumed deterministically to be single events.

Extreme wind speeds and gusts

The short-term extreme wind speeds averaged over 3 seconds (gusts) are derived from the reference wind speed. The so-called *50-year gust,* the highest wind speed, which is exceeded only once within a period of 50 years, is obtained from:

$$v_{e50}(z) = 1.4 \cdot v_{ref} \left(\frac{z}{z_{hub}}\right)^{0.1}$$

The so-called *annual gust* is:

$$v_{e50} = 0.75 \cdot v_{e50}(z)$$

where z is the hub height.

It is assumed that the annual gust only takes place in combination with a limited deviation of the wind speed direction, this means short-term deviations of of $\pm 15^0$.

Gusts occurring with increased frequency in operation are called "extreme operating gusts". They are calculated from the turbulence model in dependence on the rotor diameter according to IEC.

To account for the turbulence distributed over the rotor-swept area and unevenly, a so-called “coherent turbulence function” is also stipulated according to the IEC standard. The extreme coherent gust is to be assumed to have a speed of 15 *m/s*. Beyond that, it is to be combined with a uniform change in wind direction within 10 seconds.

In some older national standards such as, e.g. at the Germanischer Lloyd, the gusts are also still calculated with a gust factor. The positive gust is defined as:

$$v_B = k_b\, \bar{v}_W$$

Whereas the negative gust is:

$$v_B = \frac{1}{k_b}\, \bar{v}_W$$

The gust factor is taken into consideration by:

$$k_b = 1 + \frac{v_B}{\bar{v}_W}$$

The gust amplitudes exceeded with a probability of once annually ("normal operating gust") are defined as 9 m/s. Gusts which are exceeded only once in 50 years ("extreme operating gust") are defined to have an amplitude of 13 m/s.

Extreme changes in wind direction

Extreme changes in wind direction within a range of seconds can cause extraordinary loads. According to IEC 64100-1, extreme changes in wind direction within 6 seconds are calculated in dependence on the standard deviation of the turbulence and on the rotor diameter. They are to be specified as annual and 50-year events.

Extreme crosswind

The load assumptions must take into account an extreme crosswind profile as a 50-year event. This requires the assumption of an asymmetric rotor inflow produced within a period of 12 seconds both in the vertical direction (vertical wind shear) and in the horizontal direction. The shear to be assumed is calculated in dependence on the turbulence, the rotor diameter and the rotor hub height.

6.4.5 Other Climatic and Environmental lnfluences

Climatic parameters and environmental influences other than wind can affect the loads acting on a wind turbine. The limits are specified in the IEC 64100-1. The essential impacts are:

Temperature range

The verifications of strength should be carried out for a temperature range of -10°C to +40°C, In the case of special operating conditions (e.g. "Arctic climate"), the appropriate individual verifications must be made.

Air density

The calculation of aerodynamic loads is based on the assumption of the air density of the standard atmosphere (at sea level):

$$\varrho = 1.225\ kg/m^3$$

Relative humidity

The humidity of the air is of less influence under normal atmospheric conditions. According to IEC a value of 95% is acceptable.

Solar radiation

The solar radiation is assumed to be 1000 W/m² (Central European conditions).

Ice accretion

One of the environmental factors which may contribute to extraordinary loads is the build-up of ice on the rotor blades. But even thick ice formations on the rotor blades do not cause the danger of severe failure loads. Similar to aircraft wings, aerodynamic lift is reduced, with the consequence that rotor performance is reduced, and with it the aerodynamic loading (see Chapt. 18.8.2). The load assumptions distinguish between rotating parts (rotor) and non-rotating parts. For the non-rotating parts, an ice accretion of 30 mm is assumed. For the rotor blades, a varying mass distribution of the accreted ice from the root of the blade to its tip is assumed, and a difference in ice accretion between the individual blades [2].

Salt content of the air

The salt content of the air requires special design features in the area of cooling and ventilation and, naturally, special methods for the surface treatment of steel components. This is particularly true in the off-shore region.

Bird strike

One load case which is fortunately very rare can be caused by a large bird colliding with the rotating rotor. To take this hazard into consideration, the earlier Swedish load assumptions suggested some assumptions about impact velocity and bird weight [13]. The resulting impact may be of significance for the dimensioning of the rotor blade shell.

Orographie influences

The influence of the orographic situation on the wind speeds (wind flow over hills and mountains) must be taken into consideration above a certain, predetermined influencing quantity.

Earthquakes

For installations in hazardous regions with a risk of earthquakes, the local building regulations concerning earthquake protection must be consulted.

6.4.6 Other External Conditions

In order to provide a complete overview of all conceivable loads, the load assumptions require the consideration of other external conditions. In addition, the entire life cycle from the assembly of the plant through its erection at the site up to its operating and repair conditions must be taken into account. With respect to its operation, in particular, the following external conditions must be noted:

Influences from the grid

IEC 64100-1 mentions the most important electrical parameters such as voltage, frequency and the shut-down characteristic of the turbine with the associated tolerances with regard to the presence of any loads from the grid. If these tolerances are exceeded, the presence of special loads having their causes in the electricity grid cannot be ruled out. At this point, reference should also be made to the grid connection regulations of the power companies (see Chapt. 10.5.2). Variable-speed installations with their "soft" grid coupling are largely protected against loads from the electricity grid.

Influence of adjacent wind turbines

The turbulence intensity is assumed to have values of 16 and 18% at rotor hub height in the IEC load assumptions. But it must be taken into consideration in this context that when wind turbines are erected in close proximity to one another, i.e. in a wind farm, the turbulence intensity is increased in the field (see Chapt. 18.3). Although the 02/1999 issue of IEC 64100-1 does not yet contain any specifications for taking these influences into account, an appropriate approach is proposed in the DIBt Guideline according to which no verification is required if the turbines are spaced apart by more than eight times the rotor diameter. If the distance is less, as it is in many wind farm installations, a method for calculating the increased turbulence intensity is specified [2]. It is common practice to perform an individual turbulence study for larger wind park installations, in some countries it is required in the building permission.

Other influences

IEC 64100-1 and the DIBt Guideline both contain a number of further notes regarding any additional loads to be taken into consideration under certain circumstances. Without claiming completeness, examples of these are:

- Wind loads during assembly and repair
- Loads from uneven mass distribution (rotor)

- Pressure of soil and ground water on the foundation
- Structural inaccuracies in tower and foundation.

These items are not covered by any generally valid standards, reference being made instead to the need for individual consideration.

6.4.7 Safety Factors

Safety factors have the purpose of compensating for inaccuracies in the load assumptions and calculating methods, structural inaccuracies and, not lastly, for deviations in the actual strength values from the specified material characteristics. The safety factor is the ratio of the design value to the calculated or specified value. With respect to the loads, the design value is the result of multiplying the calculated value by the safety factor to be assumed. With regard to the material parameters, the design value is formed from the specified value divided by the safety factor. Defining meaningful safety factors initially requires a classification of the consequences of the failure of a component. According to IEC 64100-1, the components are graded in two classes with respect to their "partial safety factors" or "potential safety factors":

- "Fail-safe" components, the failure of which is absorbed by a safety system and does not lead to any severe damage on the wind turbine,
- "Non-fail-safe" components, the failure of which leads to severe damage.

In addition, higher safety factors are defined for the limit loads (fracture/failure of stability, critical deformations) than for the fatigue loads. Table 6.19 contains the safety factors for the design loads, to be specified according to IEC 64100-1:

Table 6.19. Partial safety factors for design loads according to IEC 64100-1 (simplified)

	Load Cases		
Source of loading	Normal- and extreme loads	Technical faults	Transport and erection
Aerodynamics	1.35	1.1	1.5
Operation	1.35	1.1	1.5
Gravity	1.1 (1.35*)	1.1	1.25
Inertia	1.25	1.1	1.3

* factor increased to 1,35 if masses are not determined by weighting safety factors

The safety factors for the material parameters depend on the type of material, on the one hand, and, on the other hand, on the type of loading. They must be specified in close relationship with the material standards. It is necessary to observe the national standards such as, e.g. DIN 18 800 for structural steel or DIN 1045-1 for reinforced concrete. IEC 64100-1 generally recommends a value of not less than 1.1 for the main strength values but values of 1.0 are also permissible for the fatigue strength.

When defining the safety factors it may be tempting to compensate for a less accurate calculation by applying high safety factors. According to all previous experience, this strategy will lead to success only in small installations, if at all. The larger plants must be loaded up to the limits of the strength of the material or of the component stiffness if it is intended to keep the building masses within tolerable limits. High building masses decrease the stiffnesses and increase the forces of gravity. The attempt to compensate for the associated increased loads by using higher safety factors, in turn creates a vicious circle at the end of which the structural safety is lower instead of higher. In the case of dynamically highly stressed systems, which undoubtedly includes wind turbines, the structural safety can lastly be achieved only by greater understanding of the loads involved and of the structural dynamics (s.a. Chapt. 6.7.2).

6.5 Operational Status and Load Cases

For a machine with moving parts, the condition of the loaded system is a decisive criterion for the stresses occurring during the loads acting on it from the outside. The load cases in the narrower sense are, therefore, produced by connecting the external conditions with the operating states of the wind turbine. In this context, it is not only the operating states per se which must be considered but also other states which may occur within the entire life cycle of the product. States which become special "load cases" may occur during transport and assembly, and possibly also during large repair processes. On the other hand it would be nonsensical, however, to produce such states which then become the dimension-determining load case for the components. For economic reasons, the load cases should be restricted to those which are absolutely necessary. These are the operating conditions and the abnormal occurrences which can be expected with a certain probability.

The basic structure of the link between external loads and operating conditions and the structural stresses to be expected in it becomes clear in Table 6.20.

Table 6.20. Basic load case system and types of stress in wind turbines

		Operational status	
		Normal Operation	Techn. Fault
Wind conditions	normal	Fatique	Ultimate loads
	extrem	Ultimate loads	☒

6.5.1 Normal Operation

The loads to which the wind turbine is subjected under "normal" operating conditions are mainly relevant to fatigue life. The main causes are the high load cycle numbers of the alternating bending moment resulting from the dead weight of the rotor blades, occurring with each rotation of the rotor, the asymmetric aerodynamic forces acting cyclically through the rotation of the rotor and the ever-present wind turbulence. The loads are therefore largely covered with respect to fatigue strength by the load cases in normal operation. The individual load cases are distinguished by the operating cycle of the turbine. The starting point for defining the load cases is the frequency distribution of the wind speed on which the design is based, and the operating cycle of the turbine.

Power production

The range of wind speeds within which the turbine is operated is divided into "classes", each of which is characterised by a characteristic wind speed:

- cut-in wind speed
- partial-load wind speed
- rated wind speed
- full-load wind speed
- cut-out wind speed.

For each of these characteristic wind speeds a load case group is formed. The associated number of load alternations is derived from the fraction of time each wind speed class occupies within the wind speed distribution and from the number of rotor revolutions in these time segments. Considering the turbine's design life, this implies, for example, 10^7 to 10^8 load cycles for the bending stress of the rotor blades.

The asymmetrical flow conditions for the rotor and the random wind speed fluctuations and the loads resulting from any malfunctions are added to this "basic load spectrum". Having regard to the fatigue strength, the influence of the flow around the tower must not be forgotten. The loading by the flow around the tower occurs with the number of load cycles of the rotor revolutions during the life of the turbine for each individual rotor blade. For the total rotor force, this number is multiplied by the number of rotor blades.

Start-up and shut-down of the rotor

Rotor start-up and shut-down involve special load cases and load changes. These events occur so frequently during the life of the turbine that it must be assumed that they have an influence on fatigue life. They do in fact also represent a group of load cases, as different starting conditions with regard to wind speed, rotor speed or even blade pitch angle must be considered. When the rotor in wind turbines with pitch control starts up, the rotor blade pitch angle is either in the feathered position or in the starting position.In both cases, a more or less large component of the bending moment acts around the softer flapwise axis due to the inherent weight of the blades. If it occurs often enough, this special load case can be significant to the overall fatigue loading.

In larger wind turbines, the normal shut-down of the rotor is controlled by means of blade pitch control as the rotational speed varies, so that no special loads are involved. One exception is fast braking, the "emergency shut-down", where the reversed aerodynamic thrust can cause increased loads.

Parked rotor at extreme wind speeds

It is generally when the rotor is parked that the wind turbine has to cope with the highest wind speed, the so-called *survival wind speed.* For turbines with pitch control it is assumed that the rotor blades are in the feathered position and that the rotor is aligned with the wind. Under these conditions, the load level is much lower than under cross-wind conditions. Naturally, the precondition for this is that the yawing system and the blade pitch control are functional when the survival wind speed occurs.

In the case of fixed-blade small turbines, this problem does not occur. The strength of the turbine must be verified with rotor blades under cross-wind conditions. The assumption of a correct drag coefficient is of essential significance here. For blades subjected to a cross-wind the c_D-values range from 1.3 to 1.8.

Some wind turbines, e.g. Enercon turbines, do not stop the rotor at extreme wind speeds. The turbine continues to run with a particular blade pitch angle and at a reduced speed. In this state the loads on the turbine are no greater than with the rotor blocked. In addition, it considered to be an advantage that when the wind drops, the turbine can continue to run again at full power within a very short time without loss of energy due to cutting-in and cutting-out processes.

6.5.2 Technical Faults

Technical faults and defects can subject the wind turbine to additional loads not covered by the other load cases. It can be assumed that most technical defects, in as much as they are relevant to operational reliability, lead to an emergency stop of the rotor via a safety system, so that these types of defects do not result in any "extraordinary" loads. On the other hand, some malfunctions are possible which cause abnormal loads on the structure before the rotor shuts down. These events must be recognised and included in the definition of load cases. Thus, a theoretical *failure mode and effects analysis* should be carried out for reliability-related areas of operation, such as blade pitch control and the rotor brake systems, at least in larger turbines.

Rotor emergency stop

Most technical failures will trigger the rotor emergency stop via the safety circuit, but the abrupt deceleration of the rotor results in an extraordinary loading situation for the wind turbine. With large rotors and under certain circumstances, this situation can increase the bending stress on the rotor blades up to the strength limit. In the case of a defect, for example a loss of the electrical system (generator release) or a fault in the control system, the rotor blades must be pitched very rapidly towards feathering to prevent rotor "runaway". For this, the blade is pitched so fast that, for a short period of time, the rotor blades are subjected to negative aerodynamic angles of attack. The aerodynamic thrust then acts in the opposite direction. If the rotor blades are positioned at a cone angle to each other, the bending moments from thrust and centrifugal force are superimposed in the same direction. Instead of compensating for each other as in normal operation, they add up with the consequence of an extreme bending moment on the rotor blades. A very careful analysis and optimisation of the emergency shut-down procedure is required in order to remain within the given load limits under these conditions.

Control system fault

In turbines with blade pitch control, a failure in the control system can lead to a pitch angle which is inappropriate for the operating condition. This is directly associated with special aerodynamic loads and indirectly with other consequences, such as rotor overspeed.

A fault in the control system or in the yaw drive can result in extreme cross-winds acting on the rotor. Loads due to extreme cross-wind angles or yaw angles must, therefore, be seen not only against the background of extreme meteorological conditions but also with a view to technical defects.

Generator short-circuit

A short circuit in the electrical generator causes an extreme load on the drive train. The generator short-circuit torque can amount to up to seven times the value of the rated torque (Chapt. 9.1). However, the maximum torque is limited to a low value by the coupling existing between the gearbox and the generator, usually to 3- to 4-times the nominal torque (s.a. Chapt. 8.9).

Rotor overspeed

Rotor overspeed in most cases is a consequence of other faults. Defects in the blade pitch control or a sudden loss of the electrical load, for example in case of a power system shut-down, can cause the operating speed of the rotor to be exceeded. Rotor "runaway" is basically the most severe safety hazard in a wind turbine (Chapt. 14.7).

A large enough safety margin between the permissible operating speed and the "maximum speed before fracture" is therefore required. For large wind turbines this margin is relatively small, in the order of 50 % of the rated speed. A greater safety margin would increase the mass of the rotor blades to a non-economical limit. Therefore the reliability of the rotor blade feathering system is very important to ensure the stop of the rotor in a case of emergency.

Rotor unbalance

The mass balance of the rotor blades has to be checked very carefully in the manufacturing process. However defects during operation for example in the case of damage to the rotor blades, loss of a structural part or the formation of ice on the rotor blades, an unbalance of the running rotor must be expected until the rotor stops.

Therefore, a certain unbalance mass must be assumed, the magnitude of which must be related to the size of the rotor. The resultant load case must be verified with respect to strength as well as any vibration problems which may be present.

Other situations

Besides the technical faults mentioned other situations can occur, which can cause extra loads. The IEC standards and the regulations of DIBt include further references to those events.

6.6 Structural Stresses in the Wind Turbine

The external loads acting on a system, and possibly also internal states of stresses, are transformed into material stresses through the dimensioning of the components. The required, load-bearing material cross-sections are then decided by the permissible material parameters. In the previous chapters the external loads and the circumstances where the loads act on the wind turbine were outlined. The logical next question is what stresses, deformations and stability problems the loads cause in the structure and the components of the wind turbine.

6.6.1 Kind of Stressing

In principle the structure and the components of a wind turbine must be dimensioned with regard to their loading with the following criteria:

- Ultimate limit states of carrying of strength and stability
  These are understood to be *limit loads* which lead to failure of the strength of the structure. They are primarily loads which trigger tensile stress, compressive strain and bending stress. Apart from this, there is also the so-called *failure of stability* in the form of *buckling*, for instance in thin-walled tubular steel towers, and kink in long, slender mechanical transmission elements, and, not lastly, the *tilting* of the entire system.

- Material fatigue
  Persistent, alternating stresses will lead to a fracture of material only after a certain period of time. Apart from the magnitude of the load, the number of load cycles within a given period, the design life, is of decisive importance here. The so-called *Proof of Service Strength* must be provided for this period.

- Limit states of operating capability
  Even if there is no structural failure, unacceptably large deformations of the components may restrict, or render impossible, the operating capability of the system. Deformation of the rotor blades is a typical example: it can become so great that the blade tips have no more clearance from the tower.

There is no a priori answer to the question of which of these requirements determines the dimensioning of the various components of a wind turbine. It depends on the conceptual design of the wind turbine and the design of its components. Nevertheless, for a common design there are experiences which can serve as reference values (Table 6.21).

Table 6.21. Design drivers for the main wind turbine components [14]

Component	Design Drivers		
	Ultimate Load	Fatigue	Stiffness
Rotor			
Blades		●	●
Hub		●	
Drivetrain			
Low-Speed Shaft		●	
Gearbox		●	
High-Speed Shaft	●		
Nacelle			
Bedplate			●
Yaw Drive	●		
Tower	●		●
Foundation	●		

In principle, the structural dimensioning of wind turbines is treated mathematically by the same methods as those known also from other fields of technology. There are no special features with regard to the materials used. The treatment of highly loaded, fibre-reinforced composite materials as used for rotor blades, for example, is "state of the art" today.

Calculating the breaking strength or the stability limits in the case of single, non-recurring loading is a traditional task related to strength. They are considered as quasi-static load cases and can therefore be treated by using comparatively simple calculation methods. They do not, therefore, require any further explanations in this book. The issue of fatigue strength represents another problem entirely, which requires "wind-turbine-specific" knowledge and will, therefore, be discussed in more detail in the next chapter.

The material fatigue due to persistent, alternating loads is determined by two decisive factors: the external loads acting on the system within the predetermined life cycle and the so-called *dynamic response characteristic* of the structure with respect to the alternating external conditions. The resultant *structural dynamics* have a great influence on the fatigue strength. Basically, the following applies: in a stiff system, all unsteady loads, i.e. the loads changing with time, in particular, must be sustained by the structure, with the consequence of rapid material fatigue. In a soft, elastic system, the alternating loads cause movements of the components and are thus absorbed by the inertial forces of the accelerated masses, the material fatigue being much less under these conditions. Calculating fatigue strength in wind turbines presents special requirements for two reasons:

With a design life of 20 years, the alternating loads, for example the cyclic bending stress in the rotor blades, resulting from their dead weight during the rotation of the rotor, but also alternating stochastic loads from the turbulence of the wind, lead to extraordinarily high cyclic load numbers. In comparison with other systems, these are at their upper limit (Fig. 6.22). For some materials such as, for example, fibre-reinforced composite materials, but also for the welded seams of steel structures, cyclic load numbers of 10^7 to 10^8 are at the limit of current experience. These uncertainties must be compensated for by particularly fatigue-resistant designs or by higher safety factors.

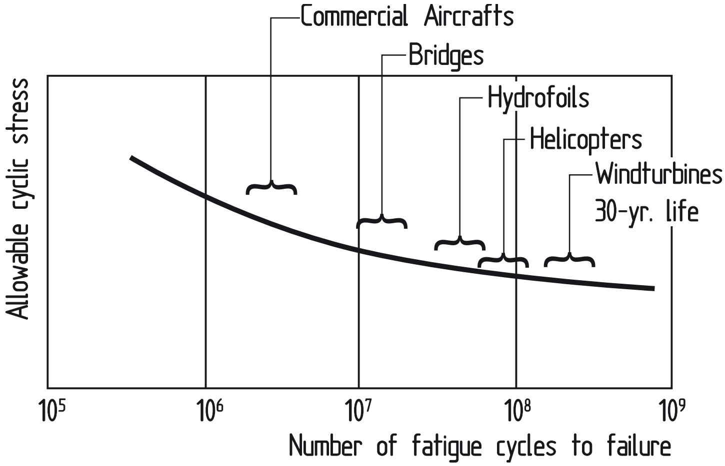

Fig. 6.22. Permissible alternating stresses and load cycle numbers of various systems [14]

The second issue is the alternating loads resulting from the wind turbulence. Mapping these loads correctly by means of a suitable turbulence model requires a profound understanding of the characteristics of wind. There are no relevant suitably comprehensive models from other fields of technology in existence. Although the influence of wind turbulence on material fatigue is known also in aeronautical engineering or in the aerodynamics of tall, slender buildings, the conditions are quite different in both fields. For this reason, the methods developed here can be translated to wind power technology only with regard to the basic assumptions.

6.6.2 Load Spectra

In simple stress situations with static loads, it is sufficient to calculate the structural strength separately for individual load situations or load cases. If a safe fatigue life is required with alternating loads, elementary fatigue strength theory assumes that stress fluctuations occur with constant amplitudes within the lifetime of a component. If the stress amplitudes are below the *fatigue strength* of the material, then the number of load cycles no longer plays a role, i.e. changes in load can be endured any number of times. If the stress amplitudes are higher than the fatigue strength allows, only a certain number of load fluctuations can be sustained, i.e. the material is only "fatigue-limited". In the case of steel, this mechanism is represented by the well-known "Wöhler-line". This fatigue model has been found useful for "normal" engineering problems.

The elementary theory is no longer adequate for designing for the fatigue strength of dynamically highly stressed systems such as aircraft, automobiles and wind turbines.

The load spectrum with regard to material fatigue consists of periodic and stochastic stress fluctuations, with varying mean values and fluctuations. The single stress situations can no longer be considered independently, but must be assessed in their totality, as a *load spectrum.* Against this background, calculating the *endurance strength* requires more complex models which can also be summarised under the title of *damage accumulation.*

The load spectrum summarises the stress situation of a component over its entire life in an idealised form. The load sequence within an operating cycle of the wind turbine, which the component has passed through a certain number of times within its life, forms the basis for the load spectrum. The progression of the cyclic bending moment experienced by the rotor blades of a wind turbine in the individual load cases serves as an example (Fig. 6.23).

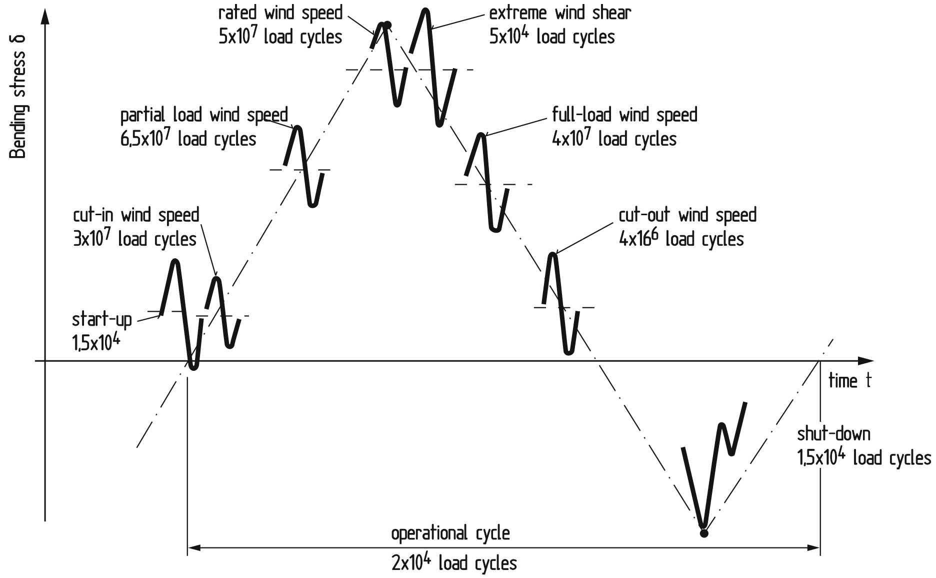

Fig. 6.23. Idealised fatigue load sequence of bending stress in chordwise direction of a rotor blade

According to the load case definition, operation under load is composed of five load cases, each characterised by a certain wind speed. During the start-up and shut-down process, the rotor blades are subjected to a higher load level as the blade pitch angle is set such that the dead weight bends around the flapwise axis. This condition has been assumed as occurring with a certain frequency in the lifetime of the wind turbine.

In full-load operation the amplitudes of the bending moment around the chordwise axis are determined primarily by the dead weight of the rotor blades. The influence of wind shear can also be recognised clearly but it must be noted that an extreme wind shear has been assumed. The effects of wind turbulence on the chordwise bending moment are only slight. It is the flapwise bending moment that is primarily affected. Naturally, the weight of the rotor blades in relation to the aerodynamic forces plays a decisive role in this.

Apart from the alternating amplitudes in the single load cases, the transitions from one load case to the next also play a role. Seen from the collective load point of view, these transitions result in additional stress amplitudes. In this example the maximum amplitude excursion is evidently created by the transition from operation at rated power to shut-down. To each load case, load cycle numbers are assigned which are deduced from assumptions about the frequency of occurrence of the operating cycle within the life span and from the proportion of time occupied by each load case in the operating sequence. They range from around 10^4 for the occurrence of rare events such as extreme wind shear, up to around 10^8 for the alternating bending load at partial-load wind speed.

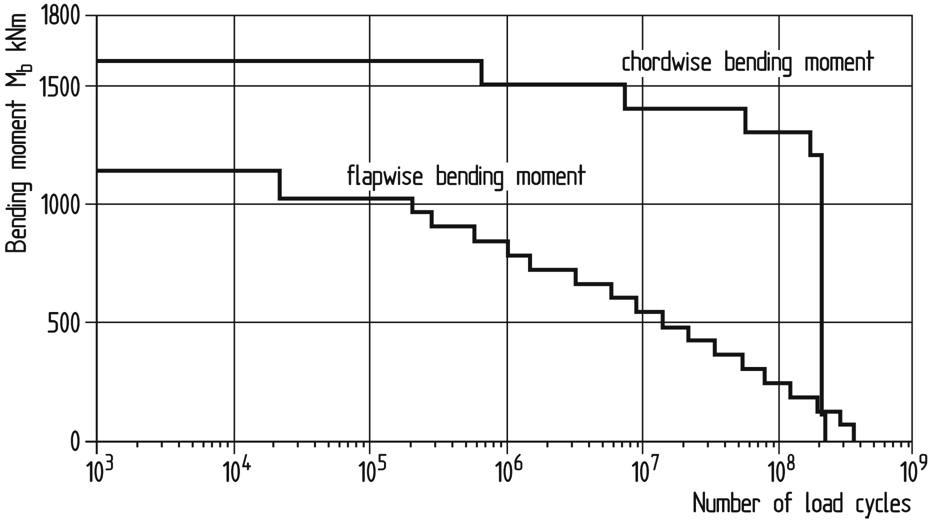

Fig. 6.24. Measured stress amplitudes (without mean value) against load cycle number measured on the rotor blades of the WKA-60 [15]

Figure 6.24 shows an example of a measured load or stress spectrum as it is normally represented. The material stress measured at the rotor blades of the WKA-60 turbine has been plotted against load cycle numbers. In the form shown, the load spectrum is referred to the period of one hour and, therefore, be projected to a service life of 30 years, corresponding to about 10^8 load cycles, for assessing the fatigue situation. The two curves for the flapwise and chordwise components of the bending stress show dearly that the chordwise bending component is almost exclusively determined by the constant amplitude of the gravitational loading, whereas the flapwise component is determined by the aerodynamic loading and hence has a varying amplitude.

Such load or stress spectra must be prepared theoretically for every structural component subjected to dynamic stress, but in any case for the rotor blades and hub, the main shaft and gear box and possibly also for the highly stressed components of the yaw system. On the other hand, the computation work must be restricted to an amount that makes economic sense. In the case of small systems, therefore, simplified methods will be used.

6.7 Mathematical Models of Structural Dynamics

The elastic components of the structure can be excited into oscillations by external forces. If the excitation frequency is the same as the natural frequency of the components, resonances will occur. The oscillation is continuously supplied with energy which leads to it building up, an effect which can lead to the complete destruction of the structure. The oscillations are only counteracted by the so-called *structural damping* which, as a rule, is very small, and possibly by some external damping such as, e.g. the aerodynamic damping with rotor blade oscillations in the flapwise direction. Freedom from resonances is thus an important criterion in the design of the structures and components. This set of problems will be discussed in greater detail in Chapter 8 "Vibration Problems".

As far as the fatigue strength is concerned, the predominant factors are the absorption of the external forces by a "yielding" of the structures and the conversion of energy into the inert masses of the components moved. This phenomenon considerably reduces the stress levels of the structure, i.e. the material stresses.

6.7.1 Functional and Structural Modelling of the Wind Turbine

One problem of structural dynamics consists in the fact that stress can be calculated only in a coherent mathematical model on the basis of the excitation, e.g. the turbulence, via the aerodynamic behaviour of the rotor and the power and speed control of the wind turbine and including the elastic properties of the stressed components. Developing such a complex model composed of several part-models is an important step in the calculation of fatigue strength. However, this also poses the first risks. The quality of the results is decided to a large extent by the simplifications and assumptions which must necessarily be made in this context.

Aerodynamic rotor model

The calculation of aerodynamic loading, both due to the steady-state flow against the rotor as well as from wind turbulence, requires an aerodynamic rotor model. Blade element theory, as outlined in Chapter 5, is a suitable instrument for aerodynamic loads from a steady-state wind flow. Dynamic loads caused by wind turbulence and the elastic response of the structure can be calculated by means of a simplified aerodynamic model. A linear analytical approach for the dependence of the aerodynamic force coefficients on the angle of attack is often sufficient (Chapt. 6.5.2).

Elastic structure model

Theoretical tools for calculating elastic structures are currently in use in many areas of mechanical engineering. They are based almost without exception on the finite-element model, with the aid of which the natural frequencies and properties of the structural components can be calculated. Knowing the natural frequencies, the dynamic responses (deformations, accelerations, stresses) under the influence of external forces can then be calculated. The computer programs based on this can also be applied to the components of wind turbines.

It is of little help to proceed on the basically correct assumption, that the dynamic response, and with it the stresses, can only be calculated correctly if the elastic characteristics of the entire turbine are taken into consideration. An elastic structural model of the entire turbine would inevitably require an enormous computational effort resulting in a corresponding amount of data, with the associated risk of missing the critical points.

It is therefore important to use a good measure of feel for how the components are dynamically coupled, in order to define subsystems with the aid of which the significant loads can be calculated. In most cases, for example, the rotor blade vibration can be considered in isolation, possibly coupled with the behaviour of the drive train in the case of the lead-lag vibration. The rotor/tower system can also be generally considered in isolation with regard to the bending vibration of the tower.

Functional model of the power control

If the wind turbine is equipped with blade pitch control and a variable-speed rotor, its functional behaviour has an influence on the loading. An algorithm for the blade pitch and speed control of the rotor is thus necessary. In most cases a linear model is sufficient for considering the influence of the control characteristics.

It is not necessary to proceed on the basically correct assumption, that the dynamic response, and with it the stresses, can only be calculated correctly if the functional and elastic characteristics of the entire turbine are taken into consideration. An elastic structural model of the entire turbine inevitably requires an enormous computational effort resulting in a corresponding amount of data, with the associated risk of missing the critical points. It is therefore important to use a good measure of feel for how the components are dynamically coupled, in order to define subsystems with the aid of which the significant loads can be calculated. In most cases, for example, the rotor blade vibration can be considered in isolation, possibly coupled with the behaviour of the drive train in the case of the lead-lag vibration. The rotor/tower system can also be generally considered in isolation with regard to the bending vibration of the tower.

6.7.2 Representation of the Wind Turbulence

There are basically two methods for determining wind turbulence by theoretical means. One is via the energy spectrum of the turbulence, the other is by means of an actual wind speed time history (s. Chapt. 13).

Independently of the chosen method, one phenomenon affecting the reaction of the wind rotor to turbulence must not be overlooked. In the open atmosphere, wind speed and turbulence are always unevenly distributed in space over the rotor-swept area. Many gusts strike the rotor not as a whole, but only on one side or only partially. This fact is significant for the response of the structure as regards the rotating rotor. The rotor blades "beat" into the gusts, i.e. the local wind speed changes, at their tangential speed.

An observer travelling with the rotor blade experiences these speed changes considerably more strongly than he would in the steady-state system. Moreover, depending on the duration of the gust and the speed of the rotor, the rotor blade can encounter the same gust several times (Fig. 6.25).

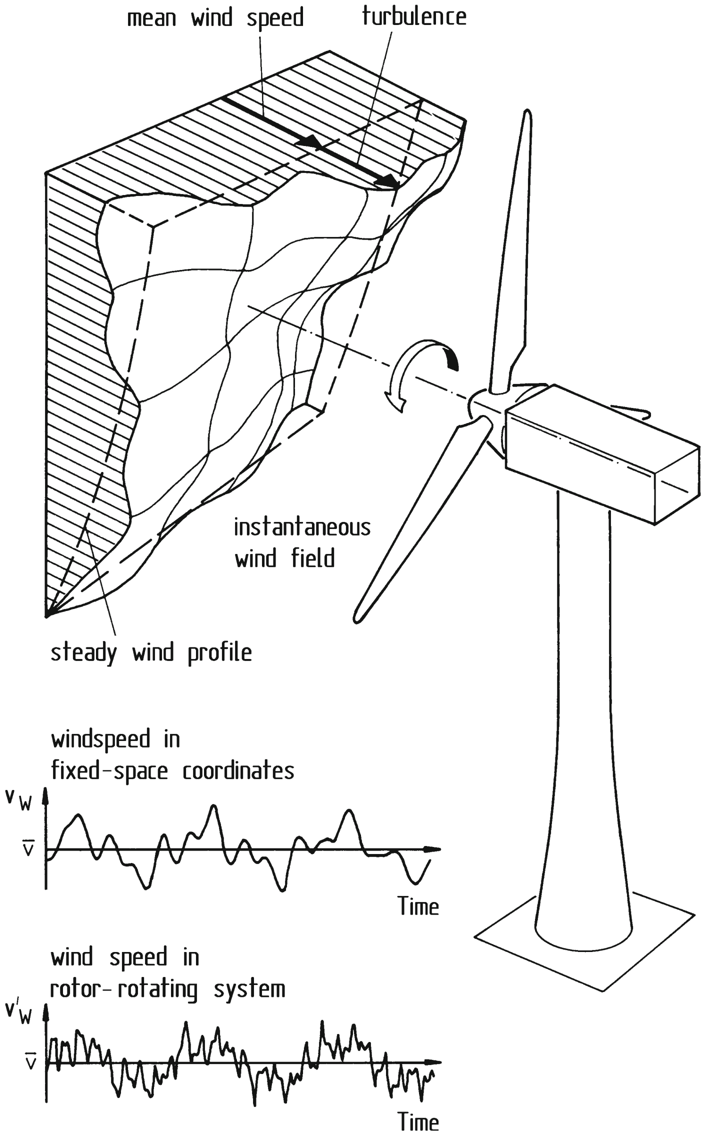

Fig. 6.25. Effect of an uneven wind-speed distribution over the swept rotor area on the upwind velocity of the rotating rotor blade

This process of *rotational sampling* is of considerable significance with respect to the effect of wind turbulence on the rotor blades, especially with large rotors. The fatiguing effect on the structure can increase by up to 50 % compared to a merely time-dependent approach to turbulences in a non-rotating, stationary reference system.

The stochastic changing loads, i.e. the turbulence of the wind, can be represented on two different ways. According to this also the methods of calculation and the presentation of the results are different. The most important models are statistically based and known as „time history or time domain method“ and „spectral method“ (Fig. 6.26).

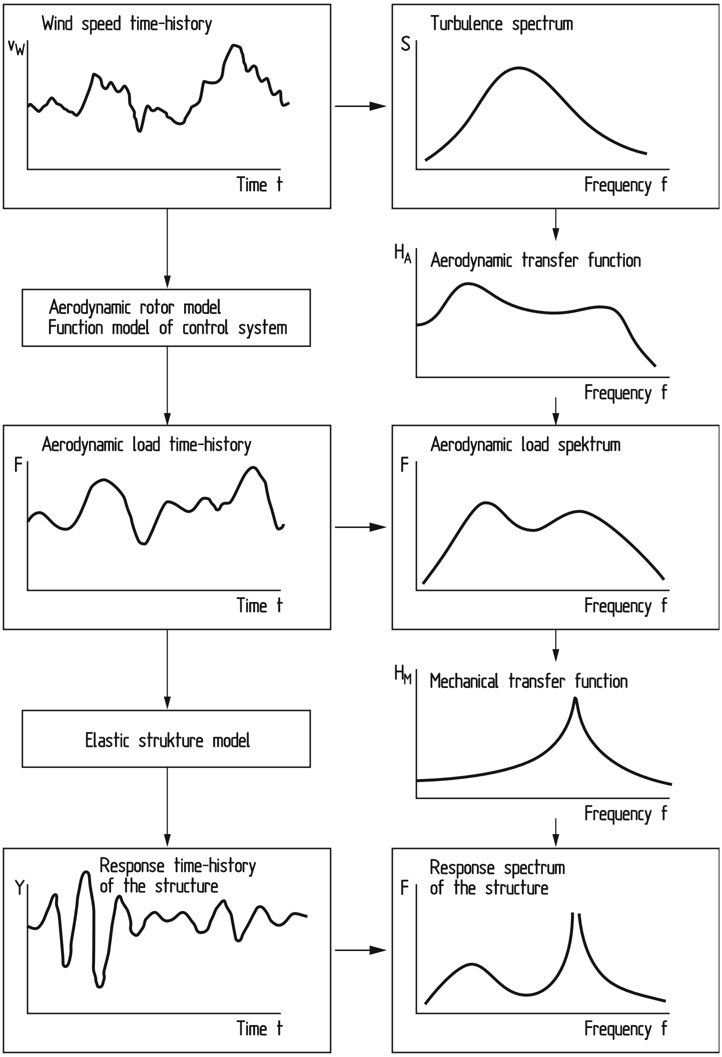

Fig. 6.26. Mathematical models for calculating the structural dynamic response to wind turbulence: time domain and spectral approach

Time history method

If the time history of the active force is known, for example the variation of wind speed with time, the resultant response of the structure versus time can be calculated. This requires an aerodynamic model of the rotor, so that the variation of the aerodynamic force can be determined from that of the wind speed. Using the elastic structure model, the response of the structure over time is obtained.

The advantage of this method is that all parameters are time-dependent, a form of presentation which is advantageous for several purposes. Moreover, functional algorithms, for example for the influence of the control system, can be taken into consideration. The influence of periodic forces, for example from the shear wind gradient or tower interference, can also be determined well by means of the time history approach. The serious disadvantage of this method is the more or less random "segment" of wind turbulence used as a basis. This does not lead to a comprehensive picture. If this were attempted, the calculation effort would become extremely high. Hence, this method is more suitable for a selective "check", rather than for comprehensive structural dimensioning with respect to fatigue life.

Spectral method

In the so-called “spectral method”, frequency-dependent representations (spectra) of forces and responses are processed instead of their progression over time. This method uses a statistical turbulence spectrum of the wind as the load input (Chapt. 13).

It must be possible to represent the structure in the form of linear or linearised equations (linear systems theory). The excitation spectrum causes excessive dynamic peaks of response in the regions of the natural frequencies of the structure. The extreme values of the required parameters (deformations, forces etc.) which are decisive for the dimensioning of the structure can be represented as follows:

$$x_{max} = \bar{x} + K \cdot \sigma_x$$

where $\bar{x}$ is the quasi-statically calculated mean value, σ_x is the standard deviation of the dynamic excursions about the mean value and K is the so-called “peak factor” based on statistical reliability calculations.

The link between the excitation spectrum and the spectra of the response reaction is established via so-called “transfer functions”. The "aerodynamic admittance" leads from the wind spectrum to the aerodynamic force parameters, "mechanical admittance" represents the link between the active forces and the deformations or stresses of the structure.

The decisive advantage of the spectral method is the reliable acquisition of the entire, real load spectrum caused by the wind turbulence. This method is thus predestined for calculating structural fatigue. The fact that the required deformation and stress parameters are only available as frequency-dependent spectra, and not as plots against time is, admittedly, a disadvantage in view of some of the technical problems at hand. For example, it is difficult to process the functional characteristics of a wind turbine methodically, with respect to the influence of the control system on the loads (functional model).

Deterministic approach

In contrast to the statistical methods described above, it is also possible to follow a deterministic approach for calculating the dynamic structure responses. As in the example of the time history method, one single event, for example a discrete gust, can be used as load input, rather than the continuous progression of wind speed (Chapt. 6.2.4). The structural response derived from this provides information on the dynamic load magnifications to be expected. From the results, all-inclusive "dynamic magnification factors" for the quasi-statically calculated stress can be derived.

The continuous nature of wind turbulence and of the response of the structure is, of course, lost in the process. It is also not possible to cover all of the load inputs with respect to the overall load spectrum by this method. Up to a certain point, one can get by with assuming a certain frequency of the various discrete events (gusts), but the validity of the results with respect to the structure's fatigue nevertheless remains questionable.

6.7.3 Analytical Approaches and Numerical Computer Codes

In the procedure for structural dimensioning, the mathematical models outlined are combined with one another (Fig. 6.26) [9]. This provides the structural loads in the form of so-called "stress resultants" at pre-defined points of intersection of the structural components as time or as frequency spectra (Chapt. 6.6.2). The combined stresses of all given load cases represent the load spectra for the individual components of the wind turbine.

The calculated material stresses are compared, as usual, with the permissible stress values. To be able to determine the permissible values, material properties and the design standards to be used, for example for the welded seams, are needed. With the consideration of *safety factors* to guard against fracture, or for some other defined threshold value, the structure can be dimensioned, or, if dimensioning has been determined, design verification can be carried out (Chapt. 6.8).

In principle analytical approaches are possible to calculate the structural dynamic stresses at least for geometrically simple structures. For example for the rotor blades, because they can be represented by a simple beam model. The first step is the modal analysis to determine the natural frequencies and mode shapes (s. Chapt. 7). The modal analysis can be based on the well known finite element calculations. The next step is establishing of the equations of motion for each element and to combine them with the boundary conditions matched at the interfaces. The equations can be solved in predetermined time steps. The result is the distribution of the loading and stress parameters over the blade length. Under simplified conditions the analysis can be carried out in an analytical form [14].

With the availability of increasing computer power numerical simulation codes for structural dynamics are widely in use. In most cases they will be based on the time domain method. In this way also non–linear effects, for example at large deformations, and non-stationary effects, for example in aerodynamics, can be included. Furthermore a great number of components can be modelled in a detailed finite-element representation (multi-body simulation). By numerical integration of the equations over the time, subdivided into short time steps, the problems can be dealt with any desired level of accuracy. A great variety of commercial available computer codes are offered for structural dynamics. They are used in nearly all fields of technology for dynamically loaded systems. In wind energy technology structural dynamic simulations become more or less mandatory in the certification process.

A critical remark should be allowed about the extensive use of structural dynamic simulations, regardingless there undisputed importance. The very complex simulation codes are not suited for finding an optimal conceptual design of a system. This task remains to the design engineer or to the design team. Finding an optimal concept includes much more aspects, like costs, manufacturing capabilities or operational issues. An optimum concept only can be based on “experience” and “creativity”. The first one is as important as the second one.

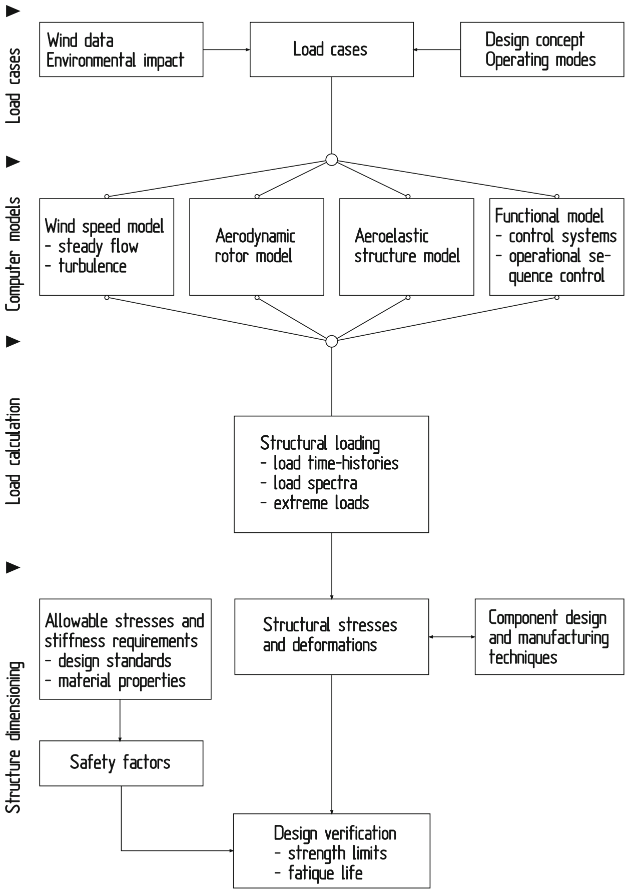

Fig. 6.27. Flow chart for calculating the loads and for dimensioning the structure

6.8 Conceptual Design Features and Structural Stresses

The design engineer, with his choice of conceptual design features, determines the loading on the components within certain limits. The general aim must be to reduce the loads to a level which is the unavoidable minimum. The loading on the rotor and the turbine in a steady mean wind and that resulting from the weight of the components is unavoidable. Loads resulting from the turbulence of the wind are avoidable to a certain degree, however. Damping these dynamic loads by suitable design features, allowing the turbine to exhibit a "softer" dynamic response, is a key problem in the design.

As a first step, it will be attempted to reduce the high alternating loads on the rotor blades. The dynamic response of the rotor to the wind gusts affects, in particular, the flapwise bending moment in the root area of the blades. This load is of decisive significance for the fatigue loading on the rotor blades.

In addition - and this aspect is just as important - the cyclically changing total rotor forces and moments must be evened out. These loads are passed on to the other turbine components and determine the dynamic load level for the mechanical drive train, the yawing system and the tower of the turbine.

The most important system features determining the dynamic load level of the wind turbine are the number of rotor blades, the function of the rotor hub in the case of two-bladed rotors, the type and quality of power control, and, not least, the stiffness of the electrical coupling to the fixed-frequency grid.

Out of these possibilities open to the design engineer, two basic philosophies emerge. On the one hand, there is the school still adhering to the old English motto: "Make it stiff and strong and you will never be wrong". The older, stall-controlled Danish wind turbines followed this principle. On the other hand, there is the endeavour to keep the dynamic response of the design and structure as soft as possible so as to reduce material stress. It goes without saying that this approach is the more promising one for large turbines even if it is associated with more development work.

6.8.1 Number of Rotor Blades

Considering the sum total of the rotor forces during a steady-state but asymmetrical wind flow, serious differences become apparent which depend on the number of rotor blades. This is clearly illustrated by the example of the aerodynamic yaw moment and the driving torque. While one- and two-bladed rotors generate considerable alternating loads with respect to the yaw moment and a pulsating drive torque, the rotor moments almost completely balance out overall during a revolution in rotors having more than two blades (Fig. 6.28). One-bladed rotors behave quite unfavourably in this respect. Their geometric asymmetry, and with it their aerodynamic asymmetry, causes extreme, alternating rotor forces and moments even with a symmetrical wind flow.

The critical influence of the number of blades becomes even clearer if the dynamic response of the elastic rotor is also considered. This is especially true of rotors with less than three blades, a fact which has long been known empirically. The deformations experienced by a rotor under the influence of external forces, primarily bending of the blades, produce inertia forces due to the structural masses being accelerated. The moment of inertia of the rotor around its instantaneous axis of motion is of importance to the dynamic response to these external loads. When the rotor is rotating, the moment of inertia changes during a rotor revolution in relation to a fixed axis when the rotor only has two blades, i.e. behaves like a rotating rod. Whereas rotors with three or more blades behave like a disk as far as the moment of inertia is concerned, i.e. are symmetrical in terms of mass, the mass of the rod-shaped two-bladed rotor is asymmetrical and its moment of inertia has a pulsating profile during a revolution. Depending on whether the rotor blades are perpendicular or parallel to the axis under consideration, the mass moment of inertia varies from a maximum to a minimum value. This phenomenon has serious consequences with respect to the dynamic re action of the rotor during excursions from its normal position.

If an asymmetrical wind flow, for example in a horizontal rotor position, causes a deflection of the rotor blades, the resultant angular velocity around the vertical axis is comparatively small, as the moment of inertia of the rotor about its vertical axis is large in this position. If the rotor continues to turn towards the perpendicular, the moment of inertia about the vertical axis reduces. Since, for physical reasons, the rotational momentum is maintained, the angular velocity around the vertical axis becomes all the greater. The consequence is a dynamically-caused yaw moment about the vertical axis. This dynamic moment of reaction reinforces the aerodynamic yaw moment already existing from the asymmetrical flow. The pitching moment, triggered, for example, by the asymmetrical flow to the rotor due to shear wind, is thus reinforced in a two-bladed rotor.

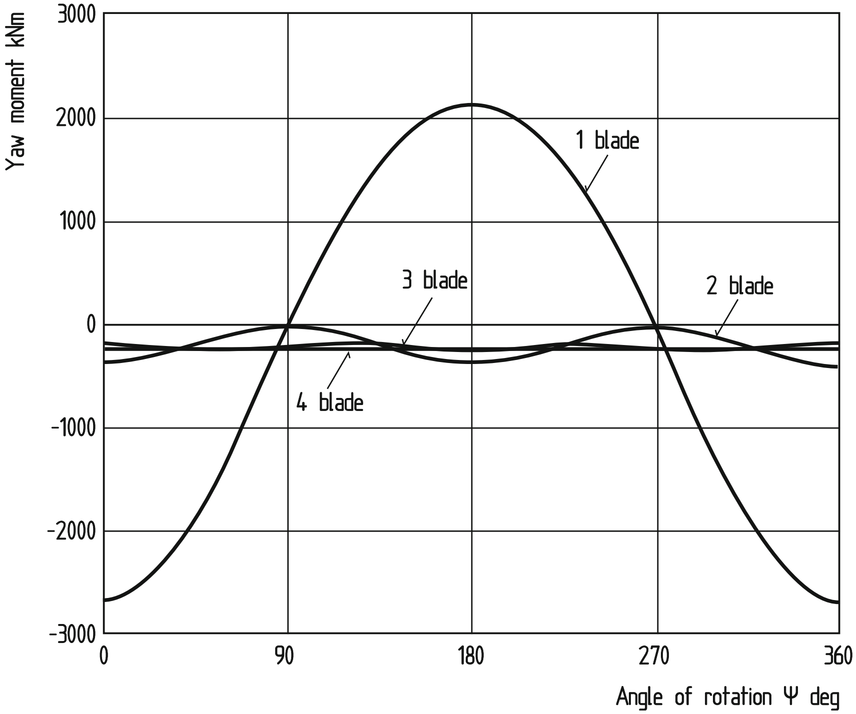

Fig. 6.28. Aerodynamic yaw moment of a rotor with different numbers of blades with an asymmetrical wind flow, calculated using the WKA-60 as an example

Hence, wind turbines with two-bladed rotors are subjected to particularly high dynamic loads if the rotor blades are joined rigidly to the rotor shaft. In order to reduce the negative consequences for the total system, either the strength and stiffness of the turbine components must be dimensioned to accommodate this increased load, or the design concept of the two-bladed rotor must be selected such that it can largely reduce these dynamic loads itself by means of an appropriate controlled compliance.

6.8.2 Rotor Hub Hinges in Two-Blade Rotors

In order to reduce the poor dynamic response of the two-bladed rotor to asymmetrical flow conditions, a series of design ideas have been proposed and to a large part also been realised, at least in experimental wind turbines. The preferred solution is the introduction of hinges, providing the rotor blades with additional degrees of freedom of movement, so that the dynamic alternating loads can be reduced in the rotor itself by "limited yielding" due to the acceleration of its own masses. The simplest way of achieving this compliance is by installing hinges between the rotor blades and the rotor shaft, i.e. in the rotor hub. Figure 6.29 shows the basic possibilities in the design of two-bladed rotors.

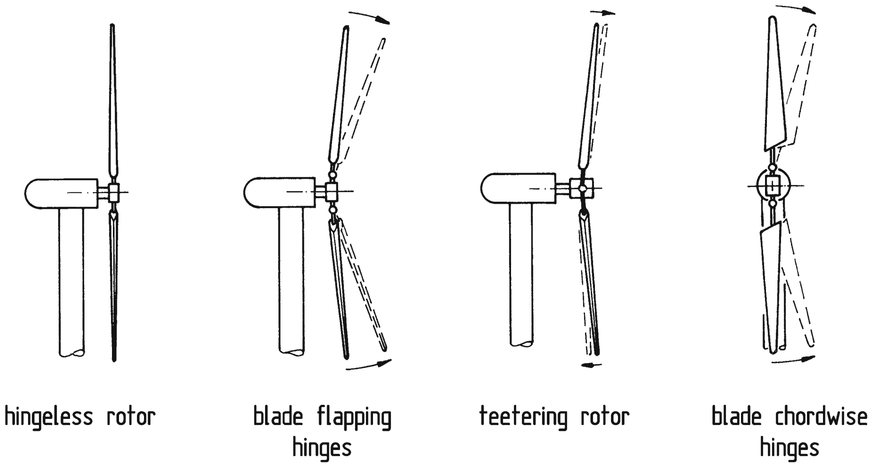

Fig. 6.29. Hingeless rotor and rotor hub hinges in two-bladed wind rotors

Hingeless rotor

The hingeless rotor, i.e. with the rotor blades joined rigidly to the rotor shaft, represents the traditional design. The old-fashioned windmill rotor has always been a hingeless rotor. This simple type is completely adequate for rotors with three or more rotor blades, even today. Two-bladed rotors, too, were built with rigid hubs for reasons of simplicity (WTS-75, AEOLUS II). The advantage is the simple construction of the rotor hub and the disadvantage is the fact that wind turbulence, in combination with the dynamic response of the two-bladed rotor which tends to amplify the asymmetrical and cyclic alternating loads, must be sustained fully by the structure. This requires a stiff design with corresponding expenditure on materials. This primarily affects the rotor blades, but also the loads on the mechanical drive train and the yaw mechanism and the tower. If the rotor is additionally subjected to tower shadow effects, the load situation becomes even more unfavourable. Hingeless two-bladed rotors should, therefore, not be set up in the downwind position.

Blade-flap hinges

Hinges permitting a limited flapping motion of the rotor blades were introduced as early as 1940 in Smith-Putnam's wind turbine (Chapt. 2.3). The main advantage of a rotor with individual blade-flap hinges is that it can evade symmetrical gusts, i.e. those striking the entire rotor area, as well as asymmetrical gusts.

One disadvantage of the flapping movement already became apparent in the turbine mentioned above. The relatively large flapping movement of the blades shifted the centre of gravity closer to the rotor axis. The conservation of rotational momentum forced the blade, which was closer to the rotational axis, to accelerate its rotational movement about the rotor axis. The consequences were dynamically produced lateral forces and torques acting on the rotor shaft. In operation, a rotor with individual flapping blade movement would, therefore, be found to be running relatively roughly. In more recent wind turbines, a blade-flap hinge has only been used on experimental one-bladed rotors.

Teetering rotor

The mechanical complexity associated with individual blade-flap hinges can be reduced by connecting the entire rotor to the rotor shaft by means of a single hinge. The rotor is thus able to perform teetering movements about the rotor shaft. A teetering hub of this type was used for the first time in 1959 by Ulrich Hütter.

The teetering rotor responds to a symmetrical loading on the rotor in the same way as a hingeless rotor. Asymmetrical loads, however, can be balanced out. The teetering rotor results in considerable improvement, particularly as far as the cyclic loads caused by the vertical windspeed profile are concerned. The unfavourable yaw and pitch moments of the rotor disappear almost entirely. Installing a teetering hinge on a two-bladed rotor achieves dynamic characteristics comparable to those of a three-bladed rotor. Hence, two-bladed rotors with teetering hubs and three-bladed rotors with hingeless hubs can be considered to be genuine alternative concepts. The teetering rotor of the former large experimental turbines was the preferred design for the large two-bladed rotors. However, the mechanical elements to enable the rotor to teeter proofed to be unreliable. In the future the load balancing of two blade rotors will be achieved by more sophisticated blade pitch control systems (see Chapt.10).

Teetered rotors with blade pitch coupling

An elegant method of restricting the flapping or teetering movements of the rotor blades while reinforcing their load-compensating effect, is to couple the teeter movement to an adjustment of blade pitch angle (Fig. 6.30). This load compensation system was used for the historical W34 wind turbine of U. Hütter in the Fifties (s. Chapt. 2.4). Coupling teetering and blade pitch movements is achieved either by means of a mechanical linkage or by suitably tilting the teetering axis with respect to the rotor shaft. This latter method is called "δ_3-coupling", a term adopted from helicopter technology.

However, the effect of blade pitch coupling depends to a great extent on the aerodynamic sensitivity of the rotor. For heavy rotors, the effect was considered too weak to justify the mechanical complexity (for example MOD-2). But also some smaller turbines with teetering rotors, for example the earlier American ESI turbines, managed without blade pitch coupling.

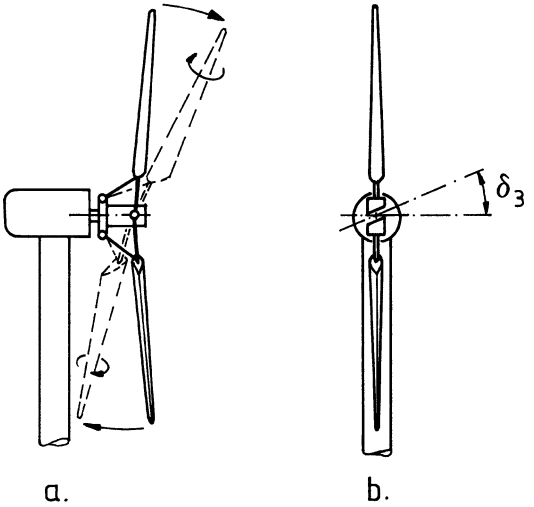

Fig. 6.30. Teetered rotor with blade pitch coupling
a) by means of a mechanical linkage
b) by tilting the teetering axis (δ_3-angle)

Blade lead-lag hinges

The theoretically greatest dynamic compliance of the rotor can be achieved by providing the rotor blades with additional lead-lag freedom. Helicopter rotors have flapping and lead-lag hinges, as is generally known. However, the mechanical complexity of these is enormous. There is the additional hazard of high degrees of instability, so that flapping and lead-lag hinges are not found in large wind rotors. An attempt in this direction was made by John Brown in 1955 with his 100 kW wind turbine, which was unnecessarily applied to a three-bladed rotor. The project turned out to be a failure for other reasons, too. It is easier to provide the rotor blades with lead-lag freedom by using a variable rotor speed, which can then be considered as a "collective lead-lag motion" of the rotor blades.

Considered all in all, mechanical hinges between rotor and rotor shaft have not been successful in large wind turbines. Apart from other problems, all systems have displayed great wear. Improvements have been achieved today due to progress in control engineering. Individual control of the blade pitch angle has a similar effect to load-compensating hinges between the rotor blades and the rotor hub. This makes it possible to control the pitch angle of each individual rotor blades periodically via the rotational cycle or, even better, in dependence on loading, in such a manner that the alternating loading can be corrected by the amplitude profile of the wind velocity or any other asymmetric rotor loading (s. Chapt. 6.8.4).

6.8.3 Stiffness of the Rotor Blades

It is obvious that the existing flexural elasticity of the rotor blades can be used to reduce the symmetrical and asymmetrical external loads. This method has been applied successfully with helicopter rotors where the introduction of elastic rotor blade root hinges allows the rotor blades to perform a flapping motion. Generally, an appropriately tuned rotor blade bending elasticity over the entire blade length can have the same effect.

On wind rotors, the practical implementation of this solution is not easy. It is difficult to achieve a high bending elasticity of the blades without coupling together several degrees of elastic freedom, including undesirable ones. The aeroelastic behaviour is then difficult to control, above all with respect to blade pitch control. In addition, the full-load deflection can become so great that the free space between the blade tips and the tower becomes a critical design criterion.

In principle, using the bending elasticity of the rotor blades specifically as a means for reducing the dynamic loading is independent of the number of rotor blades. It can also be used for reducing the level of dynamic loading for three-bladed rotors. This effect is also increasingly taken into account in the design of more recent turbines. For example, the rotor blades of the large Vestas turbines are relatively flexible. This design absorbs the loads more "softly" and saves weight in the rotor blades (Fig. 6.31).

Fig. 6.31. Vestas V80 at full power with greatly deflected rotor blades

6.8.4 Power Control System

Obviously, the aerodynamic power control of the rotor must have some influence on the loading. The first, more basic question is the question about the differences between blade pitch control and power limitation due to aerodynamic stall. In earlier years this almost amounted to a question of faith in wind energy technology but in the meantime, this conflict has lost its meaning since almost all the larger turbines have blade pitch control with a variable-speed mode of operation.

Stall-type systems with fixed rotor blades must doubtlessly withstand higher ultimate loads. As explained in Chapter 5.3.2, the rotor thrust does not drop off after the rated power level has been reached and the associated stall has begun as in the case of a blade pitch control system. This high shearing force of the rotor represents a comparatively high load both for the tower and the foundation, but also for the rotor blades themselves. An even more significant fact is that at extreme wind velocities, there is no possibility of bringing the rotor blades into a favourable feathered position and the loads become extremely high when parked. Since the dimensions of the tower and its foundations are determined by the maximum loads this will lead to greater structural masses and thus also to higher manufacturing costs. However, these parked loads can be avoided by using an active stall control system (s.a. Chapt. 5.3.3) which, on the other hand, makes it more difficult to obtain a fundamental comparison between pitch control and stall.

The situation becomes more complicated when fatigue strength is considered. The reaction to a fluctuation in the wind velocity differs greatly in the two control systems. At higher wind velocities within the range of its power rating and above, a stall-controlled turbine will always run “close to stalling”. Any short-term increase in wind velocity will immediately lead deeper into the stalling range, with the consequence that the lift coefficient will drop, and thus also the loading. For this reason, the fatigue load spectrum resulting from the wind turbulence is more favourable here than in pitch-controlled units.

Due to the inertia of blade pitching, rotors with pitch control are not capable of responding to the short-term fluctuations in wind energy which is why the fatigue loads resulting from the wind turbulence become higher. The blade pitch control can only be used for responding to relatively long-lasting fluctuations in the wind velocity (Fig. 6.32).

It must be pointed out here, however, that the comparison with stall with blade pitch control at a fixed rotor speed has become more or less academic today. In almost all of the more recent plants, the blade pitch control is associated with a variable-speed operating mode and the conditions are completely different (s.a. Fig. 6.35). Combining blade pitch control with a variable mode of operating the rotor has the effect of almost completely smoothing out the power delivery and thus also making the loading more uniform with respect to the torque acting on the mechanical drive train (gearbox).

In addition, the blade pitch control has a further option which can contribute to further lowering of the load level in future. In most cases, an individual electric pitch actuator is used today for each rotor blade. This opens up the opportunity of adjusting the pitch angle of the rotor blades individually, i.e. independently of one another. For the reasons outlined in Chapter 5.3.1 the introduction of a load-depending individual pitch control has not been introduced in series-produced wind turbines. There are ongoing attempts but the technical complexity is very high. A satisfactory solution remains a challenge for the designers.

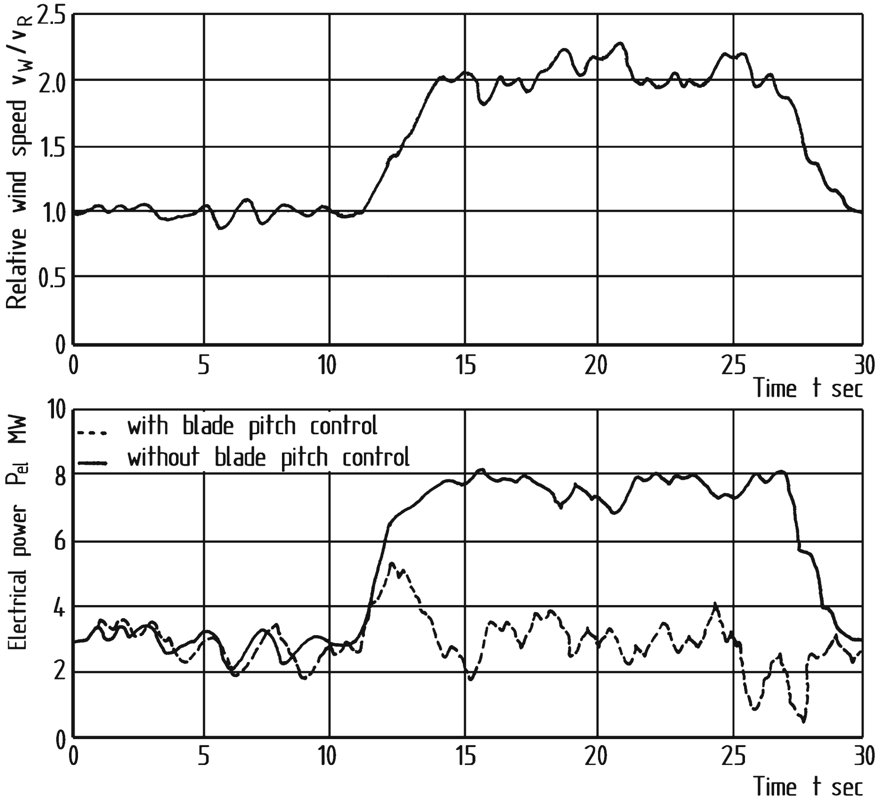

Fig. 6.32. Influence of blade pitch control on the smoothing of the electric power output with a fixed rotor speed

Using such a control method makes it possible to compensate for asymmetric rotor loads. For example, the periodically cyclic alternating loading resulting from the vertical wind shear could be compensated for by applying a cyclic change in pitch angle superimposed on the normal control function. However, a cyclic change in pitch angle would not compensate for other asymmetric rotor inflows occurring stochastically. This could only be achieved by using a load-dependent and completely individual control system for each single rotor blade.

In recent years, the leading manufacturers such as Vestas or General Electric have undertaken trials with an individual blade pitch control system. This type of control was provided for the Vestas V90 unit but has not yet been adopted in series production to the present day. As explained later an individual blade pitch control would be of special significance especially for two-bladed rotors. Large two-bladed rotors such as could be found in the early, large experimental units could be provided with such a control system and could experience a renaissance for special applications, especially for very large off-shore installations. Having this aim in mind, the basic groundwork for individual blade pitch control is also being carried out in various research institutes [16].

However, one must not overlook the difficulties of implementing a reliable individual blade pitch control arrangement. The essential problem is the availability of the correct signal as reference variable for the control. It is possible to measure the flexural loading of the rotor blades directly by means of strain gauges and to use these signals. It is also possible to use acceleration values from the tower head movement as input signals. But the practical difficulties lie in the fact that, apart from the reliability of the sensors, there are many details to be optimized. Even the location of the measurement already becomes problematic due to the continuously changing asymmetric wind loading. In addition, the rotor pitch actuator must be capable of providing an adequate pitching rate for this task. It is certain that the blade pitch drives needed for this purpose will become heavier and more expensive. In view of these manifold development tasks, individual blade pitch control will probably remain to be an option for future wind turbines used commercially.

6.8.5 Rotor Speed Flexibility and Variable-Speed Operation

One of the most important design features of an increasing number of wind turbines is the variable speed control of the rotor. This makes it possible to achieve two aims at the same time.

Firstly, if the bandwidth of the available rotor speed is great enough, the rotor speed can be adapted to the wind speed and it can be operated with its optimum tip-speed ratio, i.e. with its maximum power coefficient. This results in an increased energy supply in comparison with an operating mode with fixed rotor speed (s.a. Chapt. 14.6.3).

The second advantage lies in the fact that the rotor can store or deliver short-term power changes by deviations in its speed, i.e. by increasing or decreasing its kinetic energy like a flywheel. Having this capability makes it possible to very effectively smooth out the delivery of the electrical power and the dynamic load changes. In comparison with the aerodynamically wind-controlled operation requiring a relatively large speed range, a comparably low speed elasticity of only a few percent is sufficient to achieve a noticeable reduction in the dynamic loads. The mechanical and electrical options for a flexible-speed or speed-controlled operating mode are explained in Chapters 8.10 and 9.4. The available technical solutions behave differently with respect to the loads.

Torsional compliance in the mechanical drive train

Wind turbines equipped with synchronous generators directly coupled to the grid must have a minimum of torsional compliance and damping in the mechanical drive train. There are either torsionally elastic components which are built into the low-speed or high-speed shaft, or the gearbox must have a torsion-elastic suspension. Naturally, the effect of such measures depends greatly on the actual design adopted. Apart from torsional elasticity, adequate damping is required to keep the vibrational behaviour under control. Torsionally elastic gearbox suspensions were to be found in some large, experimental first-generation wind turbines (Chapt. 8.9). The gearbox was able to respond to an instantaneous torque peak with a torsional freedom of about 20 to 30 degrees to smooth out the load peak.

The gearboxes in today's wind turbines are mounted much more simply and inexpensively in elastic rubber bodies (s.a. Chapt. 8.8.4 and Fig. 8.44). Although this type of mounting is primarily used for preventing the transmission of structure-borne sound and for decoupling the vibration characteristics, dynamic load peaks are also removed, even if only to a limited extent.

Hydrodynamic slip in the drive train

An even more effective torsional compliance, being more strongly damped, is achieved by installing a hydraulic coupling in the mechanical drive train. Couplings of this type have a rotational slip of around 2 to 3 %, as a rule. A combination of a synchronous generator coupled directly to the grid and hydraulic coupling in the mechanical drive train has been used in the past in several types of turbines, for example the earlier Howden HWP-330 and the Westinghouse WWG-0600 or the MOD-0 turbine (Chapt. 8.9). Using the MOD-0 turbine as an example, Figure 6.33 shows the effect of a hydraulic coupling with respect to power output smoothing. Drive trains including a hydraulic coupling are also found in some recent designs (General Electric). Obviously the possibility of using a synchronous standard generator is considered as an advantage.

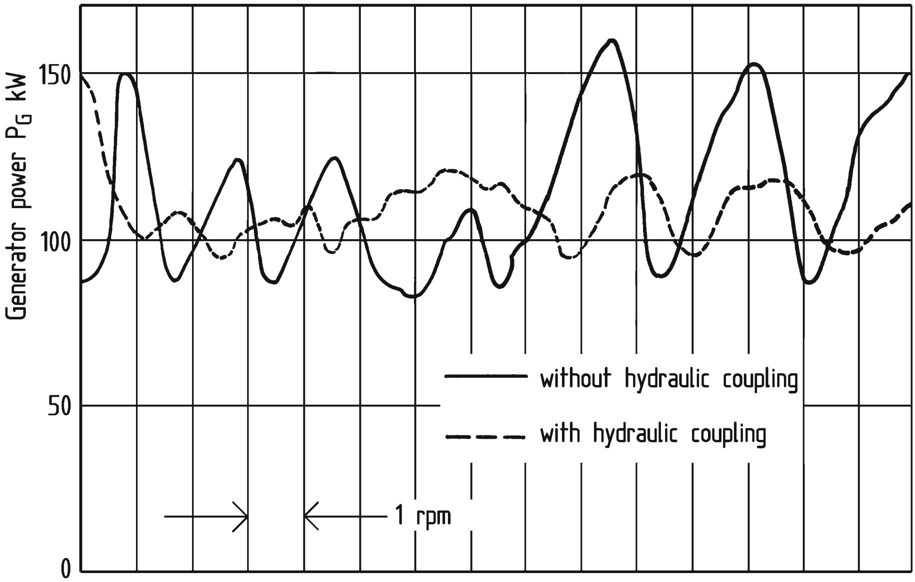

Fig. 6.33. Smoothing of the power output due to the installation of a hydraulic coupling in the mechanical drive train of an MOD-0 [17]

Electrical slip of an induction generator

In wind turbines with induction generators, loading peaks can be smoothed out via the electrical slip of the generator (Fig. 6.34). However, large induction generators only have low slip values in their standard production models (Chapt. 9.1). It is only with a slip of at least 1 to 2 % that the dynamic load level is reduced perceptibly and, at the same time, unwanted drive train vibrations are avoided.

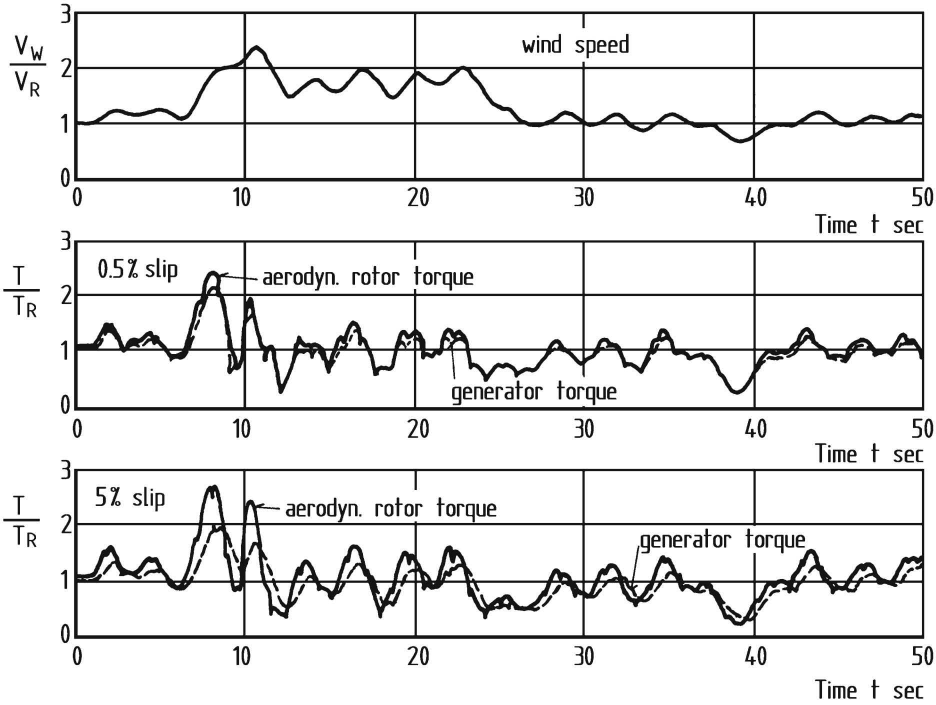

Fig. 6.34. Smoothing of power and torque with an induction generator with a nominal slip of 0.5 and 5.5 % [18]

Controlled variable-speed operation

True smoothing of the power captured by the rotor is only achieved by controlled variable-speed operation of the rotor. The generator can be operated in variable-speed mode if a frequency converter is connected (Chapt. 9.5). With this arrangement, the generator torque can be controlled to a constant value, independently of the speed, within a given speed range. The result is a complete smoothing out of the power transferred, and thus also of the loading, within the predetermined speed limits (Fig. 6.35).

The capability of a variable speed is, however, limited by the speed range implemented technically, so that larger fluctuations of wind speed cannot be compensated for. Effective smoothing of heavier wind gusts and their associated power and load peaks can only be achieved with the aid of blade pitch control. Rotor speed variability and blade pitch control should, therefore, always be considered together, as their effects complement each other. For this reason, nearly all recent turbines are equipped with both of these system features.

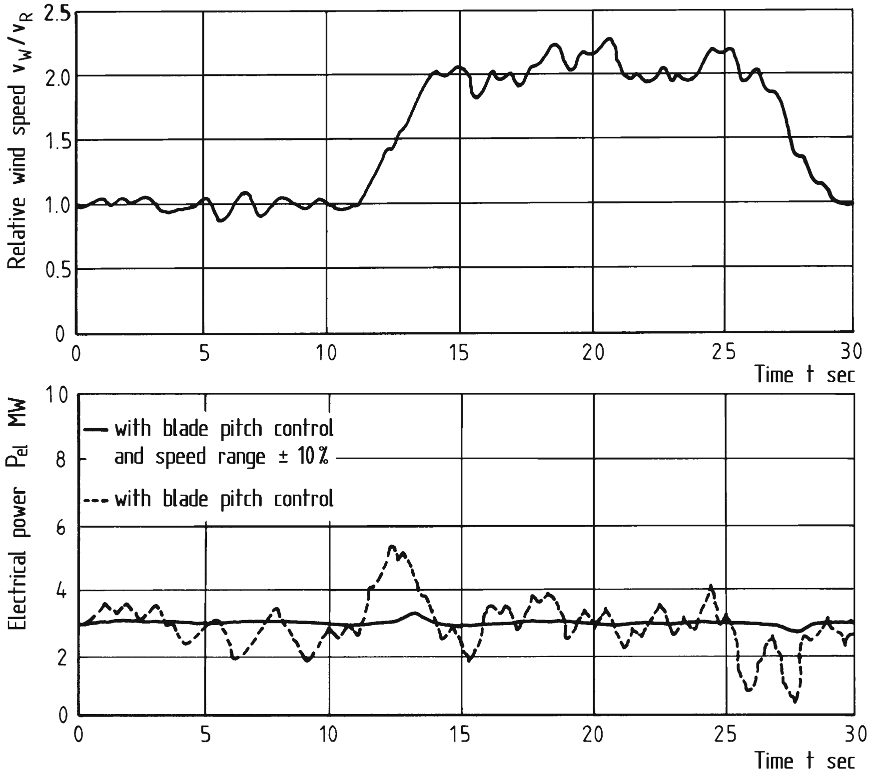

Fig. 6.35. Control of the power output with a variable-speed synchronous generator with frequency converter, using the Growian turbine as an example [18]

6.9 Measuring the Structural Stresses

The theoretical determination of the structural stresses to which a wind turbine is subjected under the different loading conditions and in the various operating modes still has its limits in spite of elaborate and complex mathematical methods. Although significant advances have been achieved in this field in recent years, a refinement of expertise, especially in the area of fatigue loads occurring in long-term operation, is essential if the weights of the components, and thus ultimately also the manufacturing costs, are to be reduced further. Apart from the development of mathematical models, therefore, the measurement of stresses actually occurring has occupied a predominant position in numerous research and development projects for many years. Some of the earlier large experimental wind turbines had literally been designed as test-beds for the investigation of loads. Such measurements are still being carried out in newly developed turbines even today.

Naturally, the experimental load investigations also include measurements and tests which can be carried out on test stands for individual components. Tests carried out on test stands have the invaluable advantage of conveying the correlation between set loads and the responses of the test objects under reproducible conditions. They are appropriate whenever unknown material properties, the interaction of different materials in a specific design, uncertainties concerning manufacturing techniques or even the verification of calculated results are to be investigated. The loads themselves must, however, be specified, i.e. their correctness must be assumed. Apart from test-bed trials with gearboxes, or total mechanical drive trains, the rotor blades commonly are subject of testing on test beds.

6.9.1 Rotor Blade Testing

To verify their mechanical properties and dynamic characteristics, newly developed rotor blades are tested on special test stands (Fig. 6.36). The static loading capacity of the blades is first verified experimentally and the precalculated stresses in the load-bearing structural elements are determined experimentally with the aid of strain gauges. The deflections measured are an additional criterion for checking the constructional design assumptions. Dynamic fatigue load spectra can only be simulated to a limited extent. The very high load cycle numbers in the lifetime of a wind turbine, combined with the associated amplitudes, can only be represented in elaborate long-term test programs. Only the critical elements of the design are, therefore, tested with a dynamic load spectrum, in the form of smaller test objects, for example the load-transferring elements between the rotor blade structure and the hub. This makes it possible to test the overall design for its fatigue life at least in critical sections.

Fig. 6.36. Rotor blade test stand at LM Glasfiber

Another important task is the determination of the most important natural frequencies. On a test stand, where the cantilevered rotor blade is fixed at the root and is induced to vibrate, both natural frequencies and vibration modes can be measured with high precision. Although the natural frequencies determined under these conditions do not correspond exactly to the natural frequencies of the rotating rotor, the predicted stiffness parameters of the non-rotating blade can still be verified in this way.

6.9.2 Data Acquisition Systems and Field Measurements

Inquiring into the loads and structural stresses actually existing is, of course, possible only on the wind turbine itself. The usual approach is to measure the deflections of the selected components by means of strain gauges and then to deduce the material stress values. However, to obtain a complete overview of the entire load spectrum requires arduous, long-term measurement campaigns the results of which only become meaningful after a large amount of data has been statistically processed. Analysing the results in detail can be very difficult. Correlating the results with the causes of the loads can only be carried out to a limited extent, as the structural deformations only reflect the sum of all loads. To isolate aerodynamic loads, for example, is extraordinarily difficult. Similar problems are presented when particular load states are to be correlated with the events triggering them, for example individual gusts.

One of the first systematic measuring programmes was carried out by NASA in the years 1977 to 1979 during a Swedish-American test programme using the earlier Danish wind turbine at Gedser [19]. From 1976 to 1986 comprehensive measurements were taken out in the American wind energy programme with the experimental MOD-0 [20]. This was followed by the publication of measurements made on the large experimental turbines such as MOD-1, MOD-2, WTS-4 and Growian [21, 22]. One of the results is shown in Figure 6.37.

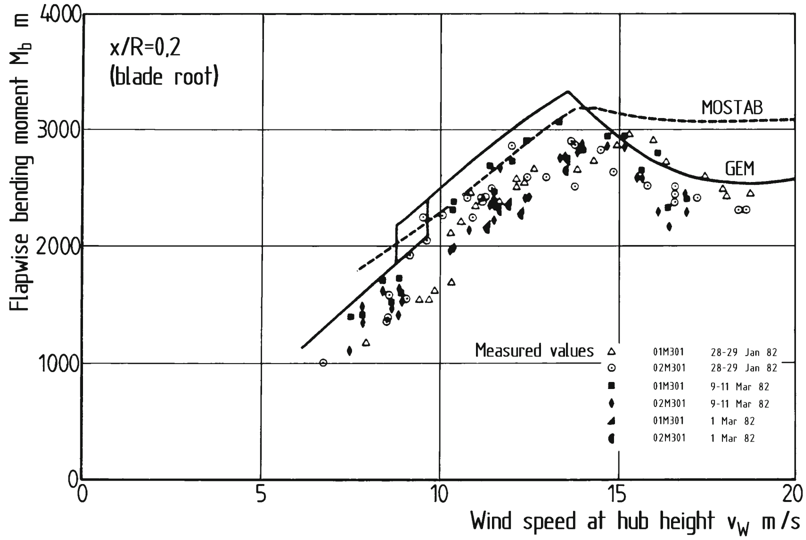

Fig. 6.37. Calculated and measured bending moments of the rotor blades of a MOD-2 [21]

The measured cyclic dynamic loads on the rotor blades of the MOD-2 correlate relatively well in the statistical mean with the values predicted by the computer programs MOSTAB and GEM. Obtaining such measurement data and the associated refinement of the computer programs are decisive prerequisites for the reliable structural dimensioning of progressive lightweight design concepts.

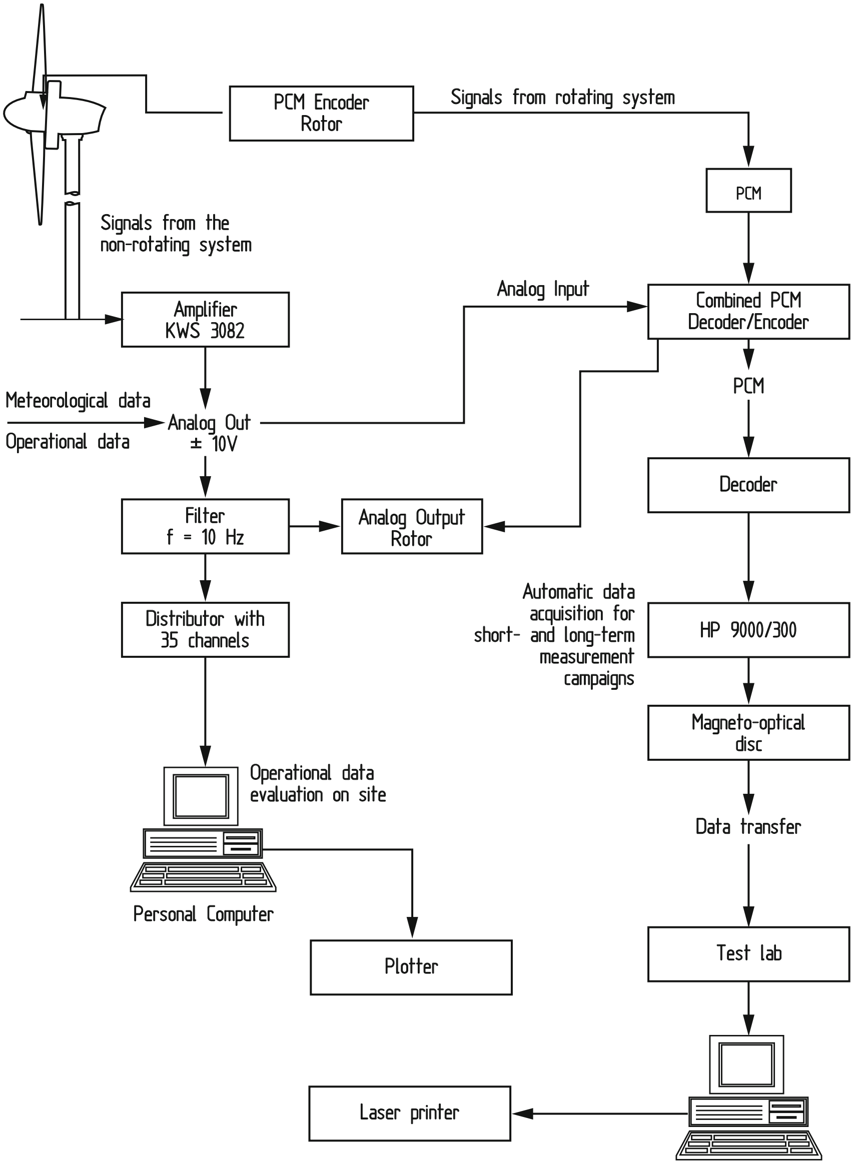

Fig. 6.38. Data acquisition system of an ENERCON E-40 prototype

Some comments must be made regarding data acquisition and evaluation in connection with load measurements taken at wind turbines. As test objects, all newly developed prototypes are equipped with elaborate measuring and data acquisition systems. In the period of test operation, setting up and operating this measuring equipment takes up a large part of the development work. This applies both to assembling the hardware and to developing the software for data editing and evaluation. Figure 6.38 shows the basic set-up of a data acquisition and evaluation system used for an early prototype of the ENERCON E-40 wind turbine.

Using various sensors and transducers such as strain gauges, accelerometers, force and displacement sensors, anemometers or instruments for measuring electric parameters, the data acquisition system can record approximately 200 test points. The measurement signals are amplified and sampled at a predetermined rate by a multiplexer. The analogue signals are then digitised and subsequently converted into a serial data stream by using PCM (pulse code modulation). PCM technology is generally required so that the data arriving in parallel from a large number of measuring points can be transferred using only one signal line. The time-consuming statistical processing of the load data acquired requires extensive computer programs. A numerical method known as the "rainflow method" has proved to be especially helpful for this purpose.

An important point must also be raised with regard to the design of the data recording and processing system. If possible, this system, used only for the test purposes, should be completely independent of the data processing system of the operational control system of the wind turbine. A functional link would give cause for grave concern for safety reasons.

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