DYNAMICS AND STRUCTURAL LOADING IN WIND TURBINES

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INTRODUCTION

The loading regimes to which wind turbines are subject to are extremely complex requiring special attention in their design, operation and maintenance. An understanding of the loadings on wind turbines and their origins, as well the turbines response to them is crucial to avoid their catastrophic failure.

Fig. 1: Collapsed wind turbine in January 2007 in Germany. Source: AP.

TYPES OF LOADS

The types of loads a wind turbine is subject to during service can be ckassified as:

STATIC LOADING

This loading is constant in time and the resulting deflection of the structure is constant and proportional to its stiffness.

CYCLIC LOADING

Two types of cycling loadings present themselves.

In quasi static cycling, the loading varies slowly enough whereas the deflection of the structure is proportional to the loading.

In dynamic cycling the loading results in a deflection related to the damping forces of the structure, particularly when the load application frequency is close to the natural vibration frequency of the structure.

STOCHASTIC LOADING

This type of loading varies in a random manner. It results predominantly from wind turbulence and is relevant to the fatigue response of the wind turbine structure.

AERODYNAMIC LOADING

This is loading derived from the force of the wind.

The rotor of a wind turbine converts the wind's kinetic energy into useful mechanical work through aerodynamic effects. The basic underlying concept is the conservation of momentum. Most of the momentum exchange takes place in the wind flow direction, although the useful power is produced by forces in the rotor plane, which is perpendicular to the oncoming stream.

A significant slowing down of the oncoming wind stream is necessary to produce useful mechanical power.

Large steady loads are generally not problematic in terms of design, and they can be reduced by blade coning, to be described later. The constant thrust loads imposed by the wind may not be dangerous as long as they are aptly accounted for at the design stage.

The cyclic and stochastic turbulence derived loads are the ones that can cause most structural failures, particularly those due to fatigue.

The rate of change of thrust T on a turbine is proportional to the square of the apparent wind velocity W:

$$\dot{T} = \frac{dT}{dt} = V^2 \rho \frac{c}{2} (C_L \cos\phi + C_D \sin\phi) \qquad (1)$$

where:

T is the axial wind thrust $[kNewton]$

V is the apparent wind speed $[m/s]$

ϕ is the inflow angle

C_L is the lift coefficient

C_D is the drag coefficient

ρ is the air density $[kg/m^3]$

c is a constant

Gusting involving rapid wind change can be hazardous particularly if the natural frequency of the turbine structure lies within the frequency range of the wind gusting.

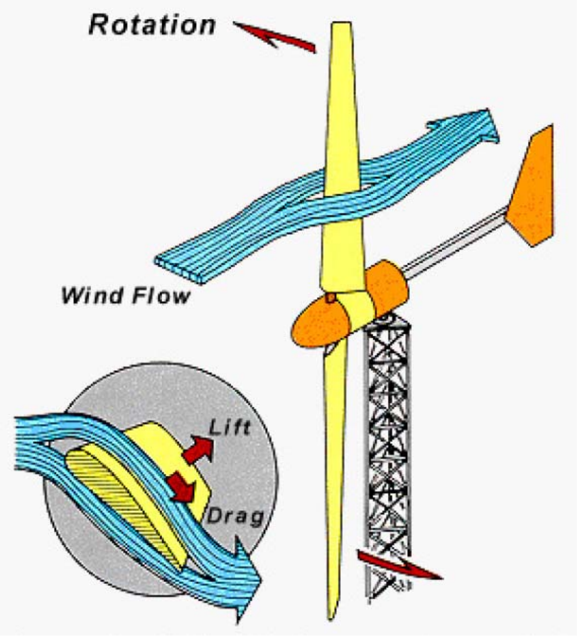

Fig. 2: Lift and drag on the rotor of a wind turbine.

Wind shear corresponding to the increase of wind velocity with height can exacerbate the effects of the wind speed due to gusting. A simple form of the basic relation governing wind shear as a function of height is:

$$V(H) = V_{ref}\left(\frac{H}{H_{ref}}\right)^{\alpha} \tag{2}$$

where:

$V(H)$ *is the wind speed at the nacelle height* $H\,[m/s]$

V_{ref} *is the wind speed at a reference height* $[m/s]$

H *is the elevation above ground* $[m]$

α *is the shear coefficient*

For a rotor with a radius of 20 meters, the tip to tip distance is 40 meters and the wind speed at the top and bottom of the blade rotation can differ by as much as 30 percent. If the shear effect coincides with severe gusting the consequences on the rotor can be serious possibly leading to failure.

The aerodynamic loading is also affected from the orientation of the turbine structure if it comes out of alignment with the direction of the wind.

Yaw misalignment is a situation arising from a discrepancy between the wind direction and the orientation of the rotor axis.

Shaft tilt is a design feature used to increase the clearance of the rotor blades from the tower in high winds. However, it can cause sinusoidal cyclic loadings to be imposed on the rotor and the drive train.

These aerodynamic loadings can become significant in rapidly veering wind conditions where a significant lag exists as the yaw mechanism of the turbine attempts to follow the wind direction.

MECHANICAL LOADING

Loadings that result from the mass or the momentum of the wind turbine's structure are classified as mechanical loads. These include:

1. Gravity Loading

Gravity can impose large fatigue stresses on the moving rotor, particularly at the region of the root and at any laminar joints. In the cases of coned and tilted rotors, the load can also be out of the rotor plane, leading to a flap wise bending around the blade's chord.

The bending moment at the root of the blade can be expressed as:

$$M_b = g \int m(r)\, r \sin\psi \, dr \qquad (3)$$

where:

m $\quad$ $is\ the\ effective\ mass\ of\ the\ rotor\ blade\ [kg]$

r $\quad$ $is\ the\ distance\ from\ the\ rotor's\ root\ [m]$

g $\quad$ $is\ the\ gravity\ acceleration\ constant$

ψ $\quad$ $is\ the\ angle\ of\ the\ blade\ with\ the\ vertyical\ direction$

2. Coning Effect

Coning which is the bending of the rotor blades in high winds introduces centrifugal force loads which act against the aerodynamic steady thrust loads, thus reducing the mean blade loading, and is a desirable feature introduced into the design of the rotor blade.

However, the removal of steady thrust loads may also cause oscillations away from the mean stress level, which could become very damaging.

3. Yaw Forces

The yaw or gyroscopic forces are significant in free yaw machines, where instantaneous yaw velocities can cause severe flapping of the rotor blades.

4. Transient Loads

Transient loads such as occur at the start up and shut down times, are dependent on the machine and control system characteristics. Inherent flaws in certain components such as a microscopic void in a slow speed shaft may result in fatigue damage under transient loading.

TURBINE DYNAMIC RESPONSE

The dynamic response of a wind turbine structure to the imposed loads affects the rotor, the power train and the structural tower. Understanding the behavior of these components under both static and varying loads is crucial to avoiding potentially dangerous responses.

It is imperative that the rotational frequency of the turbine rotor is different from any harmonics of the structure's natural vibration resonance frequency. The excitation of the resonant conditions in any dynamic structural component must be avoided, or passed through quickly at startup or shut down to avoid catastrophic failure.

The dynamic response of wind turbines encompasses different situations.

1. Static Loads

In the case of static loads the extent of deflection under a load depends upon the stiffness of the structure and the size of the load. This can described as:

$$F = -kx \tag{4}$$

where:

F is the restoration force

k is the stiffness factor

x is the deflection magnitude

The restoring force F acts in the opposite direction to the deflection x. This is the simplest model of the static response of a structure and it relies upon the assumptions that the response of the structure is linear and that the structure is allowed to reach equilibrium or its static condition balancing the applied loads and the internal reactions in the structure.

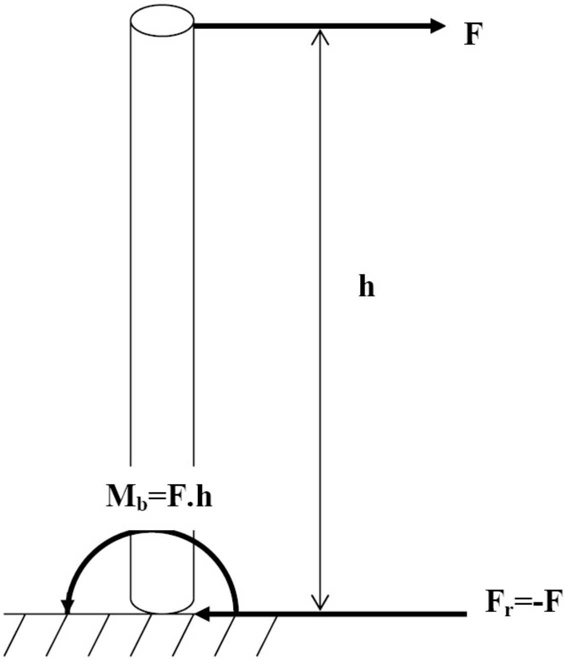

Fig. 3: Static response of a wind turbine structure to an applied constant axial load.

The static response of a wind turbine to an applied axial load F can be due to the thrust of a steady wind on the power train. For a nacelle height h, the reaction at the foundation is given by a bending moment:

$$M_b = F.h \tag{5}$$

An opposite reaction force of magnitude F_r also arises at the foundation. Equilibrium is reached for both the external applied force and the resulting moments at the foundation. The internal reactions in the structure due to the elastic effects are equal to the applied forces and moments.

The response of most materials is assumed to be linear so long as stresses in the material do not approach the yield stress of the material. The lower end of the stress-strain curve is a straight line for most common structural materials.

2. Cyclic Loads

To estimate the dynamic response of the structure, several simplifications are common:

1. The existence of a linear quasi static response
2. A linear modal response
3. A non linear quasi static response

Quasi static here means that although the structure is moving, the motion may be subdivided into small time intervals so that at each interval the system is treated as if it had reached equilibrium.

This is not totally accurate since the stiffness modulus of the structure will increase at high speeds; a situation designated as strain rate stiffening. Another reason is that the damping within the materials of the structure generates extra loads that are proportional to the rate of deformation. In addition some load arise due to air friction caused by the motion

These extra effects are usually small and so it is reasonable to neglect them in most cases.

If a structure is treated as linear, the natural modes of vibration may be found using the technique of Modal Analysis. The mode shape of a natural mode is the shape of the structure at a point in a single period of the vibration when the deformation is largest in magnitude. The frequency is the reciprocal of the time for one period of vibration.

Practically, damping in the structure changes the theoretical mode shape and the frequency of vibration. The measured frequencies are often very close to those predicted assuming a linear behavior model.

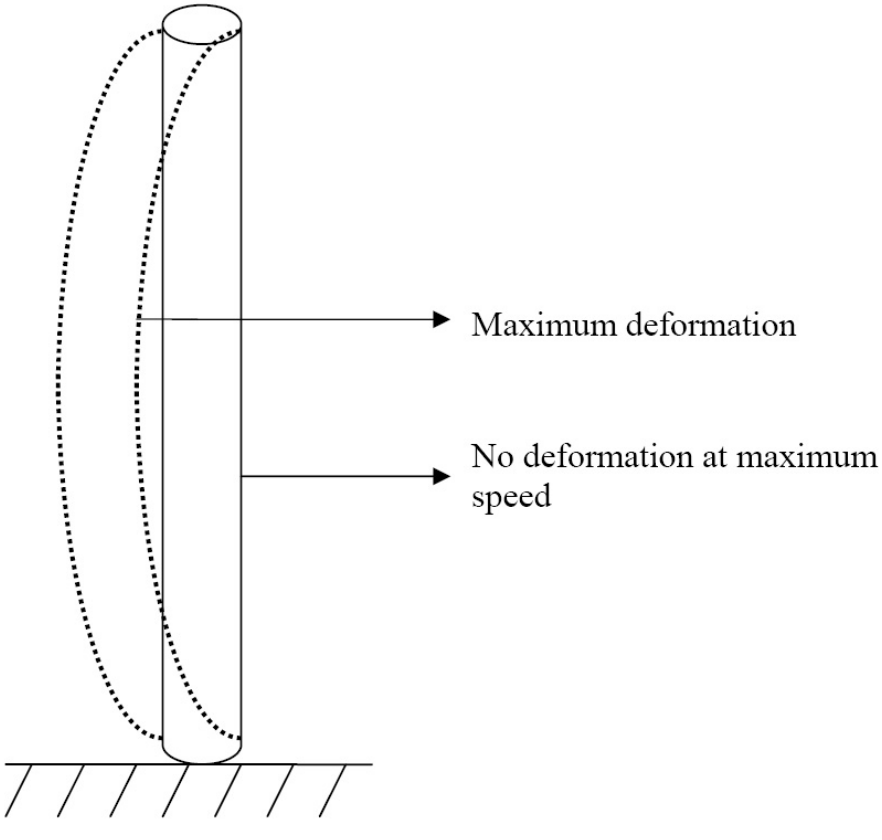

Fig. 4: Mode shape of a natural vibration mode.

The mode shape of a natural vibration mode looks like the static deformation of the structure with the practically similar. However, the structure's deformation oscillates during the vibration cycle from its static shape to its maximum mode shape. Mathematical formulae for the natural modes and frequencies of simple systems can be analytically derived.

3. Dynamic Loading

Three possible responses of a turbine tower to applied loads can occur: torsional, longitudinal and transverse. In practice, the actual response is a composite of the three responses.

If the applied load varies with a frequency approaching that of the structure’s natural frequency, then a mechanism exists whereby energy may be continuously added to the system. This leads to a progressive increase in the vibration amplitude, which continues until structural failure occurs and is called dynamic loading.

Resonant wind conditions transferred energy from the wind and waves under the Tacoma Narrows Bridge in the State of Washington in the USA leading to its collapse, and turning it into an example of resonant frequency failure. More information about the Tacoma Narrows Bridge is covered in the Appendices.

4. Vibration Damping

The damping characteristics of the structure dictate how fast the system can restore itself to the equilibrium condition when the stress forces are removed.

A structure is critically damped when the energy dissipating damping forces acting on it are just enough to soak up all the energy imparted to it by the applied load before the neutral position is reached.

Turbine blades are partially filled with a foam material, which helps to dampen the vibration of the blade under turbulent wind conditions. This prevents the blade from generating a resonant response. At the critical damping, the critical damping coefficient is given by:

$$C_r = \sqrt{4km} \qquad (6)$$

The critical damping ratio is defined as:

$$C_{crit} = \frac{C}{C_r} \qquad (7)$$

It is usually expressed as a percentage. Thus a one percent critical damping corresponds to C’ = 0.01 C_r or 1/100 of the value of the critical damping coefficient.

Instability due to aerodynamic and mechanical loads becomes more of a problem as the structures become softer as their structural modulus decreases.

The designer must ensure that the resonant frequencies are not excited excessively. Special attention must be given to the following situations and factors:

a. The start up and shut down transients.
b. The structural tower shadow effects, particularly for downwind machines.
c. Excessive torque loadings on the hub and the drive train.
d. Rotor speed variations particularly for variable speed turbines designs.

5. Tower and blade vibrations

It is important to understand the response of turbines with nacelles on slender wire-guyed towers. From the perspective of the structural tower and rotor blades, resonances may cause unwelcome noise emissions and fatigue. The tower resonances may feed back to the electrical output to the grid, causing power surges.

Structural tower and blade vibration may be studied by using the example of a simple cantilever beam. For the tower, the real system includes other factors such as inertial effects from the nacelle and resonant effects from the guy cables and the gin pole. These can be accounted for by using a partial differential modeling technique. In this case we are mainly concerned with the simple case.

In the more realistic analysis of the dynamic behavior of multiple degree of freedom cantilever systems, assumptions can be made to simplify the analysis:

a) The strain energy or potential energy in the extreme position is considered as equal to the kinetic energy in the neutral position implying that there are no damping losses.

b) The natural frequency is related to the deflected shape of the cantilever implying that there could be resonant vibration.

c) The cantilever has several natural frequencies at which true dynamic response is possible, where the applied load varies at the system's natural frequency.

d) Each frequency is associated with a particular deflected shape or the mode shape.

For a rotor blade or tower, and for more complex mode shapes, the strain energy is higher for a particular deflection in comparison to simpler mode shapes. This leads to a corresponding higher natural frequency. These mode shapes and natural frequencies are fundamental to the system, and are independent of the loading characteristics in a given vibration situation.

6. Dynamic response to stochastic random load

The stochastic random loads occur predominantly from wind turbulence. In addition to fatigue, turbulence affects many other design parameters such as the maximum load prediction, the structural excitation, and the control and power quality. The non linear nature of fatigue, there results that a doubling of the load amplitude has a very strong effect on the fatigue life.

The occurrence of high load amplitudes resulting from turbulent stochastic wind gusts reduces a structure's fatigue resistance.