Aeroelasticity and aeroacoustics of wind turbines

Aagaard Madsen, Helge

Publication date:
2011

Citation (APA):
AEROELASTICITY AND AEROACOUSTICS OF WIND TURBINES

Helge Aagaard Madsen

Risoe National Laboratory for Sustainable Energy
Technical University of Denmark

hama@risoe.dtu.dk
Outline

- Introduction to Risø DTU
- The typical wind turbine 2011
- Wind turbine loads and certification
- Aerodynamic and aeroelastic simulation tools
- Aeroelastic stability
- Wind farms and wakes
- Aeroacoustics
- New technology - outlook
- Summary
Outline

- Introduction to Risø DTU
  - The typical wind turbine 2011
  - Wind turbine loads and certification
  - Aerodynamic and aeroelastic tools
  - Aeroelastic stability
  - Wind farms and wakes
  - Aeroacoustics
  - New technology - outlook
  - Summary
Risø’s history in brief

• **1956** Peaceful utilization of nuclear energy
• **1976** Nuclear energy and other energy sources
• **1986** Energy research in general
• **1990** R&D with energy as the primary area
• **1994** State-owned enterprise
• **2000** The last nuclear reactor is decommissioned
• **2005** Impact within
  1. Technology for greater competitiveness
  2. Sustainable energy supply
  3. Health technology
• **2007** Merged with DTU (The Technical University of Denmark)
Wind Energy Division

Blade Test Center
Sparkær (Force+DNV)

National Test Station
Høvsøre

Risø

150 employees in 5 research programmes

DTU

Risø DTU, Technical University of Denmark

Ankara International Aerospace Conference, September 14-16, 2011, Ankara, TURKEY
National Test Station for Large Wind Turbines - 2007

Coastal, flat terrain
5 test positions
Max. 10 MW
Max. height 165 m

Small wind turbines at Risø - 1979
Outline

- Introduction to Risø DTU
- The typical wind turbine 2011
- Wind turbine loads and certification
- Aerodynamic and aeroelastic tools
- Aeroelastic stability
- Wind farms and wakes
- Aeroacoustics
- New technology - outlook
- Summary
The typical wind turbine design 2011

- rated power 2-5 MW
- 80-125 m rotor
- pitchregulated
- variable speed
- steel, tubular tower
- gearbox or direct drive with multipole generator
- load alleviation with cyclic pitch
- advanced control and monitoring system
The typical wind turbine design 2011

Variable speed – const tip speed ratio

Pitch regulation
The typical wind turbine design 2011

![Graphs showing wind turbine performance metrics vs. mean wind speed.](image)

11 Risø DTU, Technical University of Denmark

Ankara International Aerospace Conference, September 14-16, 2011, Ankara, TURKEY
The typical wind turbine design 2011

Old stall regulated turbine

5MW PITCH-REGULATED RWT TURBINE, 4-25m/s

500kW STALL-REGULATED TURBINE, 4-25m/s

Old stall regulated turbine
The typical wind turbine design 2011 - use of dedicated airfoil designs

- High max. lift
- High lift in post-stall to ensure smooth stall
- Transition to turbulent flow close to LE: Roughness insensitive
- Design for max. Lift-Drag-ratio / CT
- Design for low noise
- Design for high compatibility
- Design for high stiffness
The typical wind turbine design 2011 - use of dedicated airfoil designs

- **Risø-A1 (15% to 30%)**
  - Designed for stall, active stall and pitch
  - Full scale tested on a 600 kW ASR wind turbine

- **Risø-P (12% to 24%)**
  - Designed to replace Risø-A1 for pitch control
  - Used on 3 MW PRVS wind turbines

- **Risø-B1 (15% to 53%)**
  - Designed for pitch regulation variable speed control
  - Used on several MW size PRVS wind turbines
The typical wind turbine design 2011 - use of dedicated airfoil designs
Aeroelastic blade design

Aerodynamic noise

Aerodynamic performance

Aeroelastic loads

Blade structural model

Turbine cost model

Design trade-off
Blade designed for maximum aerodynamic efficiency

Table 1: Mechanical power and Thrust force for the present rotor. The IEA, 5MW RWT is included for comparison

<table>
<thead>
<tr>
<th></th>
<th>Mechanical power, $P$ [MW]</th>
<th>Thrust force, $T$ [kN]</th>
<th>$CP$</th>
<th>$CT$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EllipSys3D</td>
<td>2.015</td>
<td>426</td>
<td>0.515</td>
<td>0.872</td>
</tr>
<tr>
<td>Lifting Line</td>
<td>2.011</td>
<td>424</td>
<td>0.514</td>
<td>0.868</td>
</tr>
<tr>
<td>Actuator Disc</td>
<td>1.995</td>
<td>425</td>
<td>0.510</td>
<td>0.870</td>
</tr>
<tr>
<td>IEA, 5MW RWT</td>
<td>1.867</td>
<td>382</td>
<td>0.477</td>
<td>0.782</td>
</tr>
</tbody>
</table>
Outline

- Introduction to Risø DTU
- The typical wind turbine 2011
- Wind turbine loads and certification
- Aerodynamic and aeroelastic tools
- Aeroelastic stability
- Wind farms and wakes
- Aeroacoustics
- New technology - outlook
- Summary
Wind turbine loads and certification

Loading from:

- turbulence and wind shear in the atmospheric inflow
- wakes from neighbouring turbines
- waves
- control action, e.g. an emergency stop
# Wind turbine loads and certification

In total 1000-1500 load cases to be simulated – most 10 min. simulations

<table>
<thead>
<tr>
<th>Design situation</th>
<th>DL/C</th>
<th>Wind condition</th>
<th>Other conditions</th>
<th>Type of analysis</th>
<th>Partial safety factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Power production</td>
<td>1.1</td>
<td>NTM $V_{m} &lt; V_{hub} &lt; V_{out}$</td>
<td>For extrapolation of extreme events</td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>NTM $V_{m} &lt; V_{hub} &lt; V_{out}$</td>
<td></td>
<td>F</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>ETM $V_{m} &lt; V_{hub} &lt; V_{out}$</td>
<td></td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>ECD $V_{hub} \pm 2$ m/s, $F_{r} = 2$ m/s</td>
<td></td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>EWS $V_{m} &lt; V_{hub} &lt; V_{out}$</td>
<td></td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td>2) Power production plus occurrence of fault</td>
<td>2.1</td>
<td>NTM $V_{m} &lt; V_{hub} &lt; V_{out}$</td>
<td>Control system fault or loss of electrical network</td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>2.2</td>
<td>NTM $V_{m} &lt; V_{hub} &lt; V_{out}$</td>
<td>Protection system or preceding internal electrical fault</td>
<td>U</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>2.3</td>
<td>EOG $V_{hub} \pm 2$ m/s and $F_{out}$</td>
<td>External or internal electrical fault including loss of electrical network</td>
<td>U</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>2.4</td>
<td>NTM $V_{m} &lt; V_{hub} &lt; V_{out}$</td>
<td>Control, protection, or electrical system faults including loss of electrical network</td>
<td>F</td>
<td>*</td>
</tr>
<tr>
<td>3) Start up</td>
<td>3.1</td>
<td>NWP $V_{m} &lt; V_{hub} &lt; V_{out}$</td>
<td></td>
<td>F</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>3.2</td>
<td>EOG $V_{hub} \pm V_{hub}, F_{r} \pm 2$ m/s and $F_{out}$</td>
<td></td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td>EDC $V_{hub} \pm V_{hub}, F_{r} \pm 2$ m/s and $F_{out}$</td>
<td></td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td>4) Normal shutdown</td>
<td>4.1</td>
<td>NWP $V_{m} &lt; V_{hub} &lt; V_{out}$</td>
<td></td>
<td>F</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>EOG $V_{hub} \pm 2$ m/s and $F_{out}$</td>
<td></td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td>5) Emergency shutdown</td>
<td>5.1</td>
<td>NTM $V_{hub} \pm 2$ m/s and $F_{out}$</td>
<td></td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>6.1</td>
<td>EWM 50-year recurrence period</td>
<td></td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>6.2</td>
<td>EWM 50-year recurrence period</td>
<td>Loss of electrical network connection</td>
<td>U</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>6.3</td>
<td>EWM 1-year recurrence period</td>
<td>Extreme yaw misalignment</td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>6.4</td>
<td>NTM $V_{hub} \pm 0,7$ m/s</td>
<td></td>
<td>F</td>
<td>*</td>
</tr>
<tr>
<td>7) Parked and fault conditions</td>
<td>7.1</td>
<td>EWM 1-year recurrence period</td>
<td></td>
<td>U</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>8) Transport, assembly, maintenance and repair</td>
<td>8.1</td>
<td>NTM $V_{max}$ to be stated by the manufacturer</td>
<td></td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>8.2</td>
<td>EWM 1-year recurrence period</td>
<td></td>
<td>U</td>
<td>A</td>
</tr>
</tbody>
</table>
Outline

- Introduction to Risø DTU
- The typical wind turbine 2011
- Wind turbine loads and certification
- Aerodynamic and aeroelastic tools
- Aeroelastic stability
- Wind farms and wakes
- Aeroacoustics
- New technology - outlook
- Summary
Numerical models/tools used for aerodynamic and aeroelastic analysis at the Aeroelastic Design Group (AED) at Risø DTU

- **EllipSys2D**
  - 2D CFD code used mainly for computation on 2D airfoil sections

- **EllipSys3D**
  - 3D CFD code used for rotor computations and flow over terrain

- **Hawc2**
  - Aeroelastic multibody code for aeroelastic time simulation of wind turbines

- **HAWCStab**
  - Code for computation of aeroelastic stability

- **HAWTopt**
  - Tool for design and optimization of rotors

- **AirfoilOpt**
  - Tool for design and optimization of airfoils
Aeroelastic codes and simulations

Engineering sub-models for simulation of:

- yawed flow
- dynamic stall
- unsteady blade aerodynamics
- unsteady inflow
- tip loss
- tower shadow
- wakes from neighboring turbines
- simulation of atmospheric inflow
- hydrodynamics
- wave loads
- control

Aeroelastic codes for time simulations used by industry:

- FLEX5
- FAST
- BLADED
- HAWC2

- simulations in real time or faster
Turbulence in atmospheric inflow is the main driver of loads - rotational sampling of turbulence
Turbulence in atmospheric inflow main driver of loads - rotational sampling of turbulence

OPERATION AT 8 m/s, TI=15%

PSD of $V_y$-tip [(m/s)$^2$/Hz]

FREQUENCY [Hz]
Turbulence in atmospheric inflow main driver of loads - rotational sampling of turbulence
Simulated tower loads

The bending moment in the tower base of a 5MW turbine at 18 m/s wind speed and 10% turbulence. Solid curve bending in main wind direction, dashed curve perpendicular.
Extreme load case – gust 18-24 m/s

Wind:

Tower Mx:

Rotational speed:

Flap:

Pitch:

Figure 17 Sample simulation EOG gust during normal operation.
Results from CFD-analysis:

- Shear causes aerodynamic hysteresis effects.
- Blade loads are different in horizontal position.
- Shear causes rotor yaw loads.
Details of blade-tower interaction investigated in order to:
- study lock-in phenomena
- develop semi-emperical tower shadow model and noise model
Outline

- Introduction to Risø DTU
- The typical wind turbine 2011
- Wind turbine loads and certification
- Aerodynamic and aeroelastic tools
- Aeroelastic stability
- Wind farms and wakes
- Aeroacoustics
- New technology - outlook
- Summary
**HAWCStab2 – a linear aero(servo)elastic stability tool**

- Linearization of HAWC2 equations.
- Aeroelastic eigenvalue analysis
- Mode shape animation
- Present implementations
  - pitch and generator dof.s
  - controller model

---

![Graph](image)

- Wind speed [m/s]
- Damping in log. decrement [%]
  - Forward edgewise whirling
  - Backward edgewise whirling
  - Aeroelastic damping
  - Measurement
  - Structural damping

Generator d.o.f. for torque control

Blade pitch d.o.f.s for collective & cyclic pitch control

Tower base d.o.f.s for hydroelastic coupling
Typical modal dynamics of wind turbines

Example:

1. edgewise forward whirling
2. flapwise backward whirling
1. edgewise backward whirling
1. flapwise forward whirling
1. symmetric flapwise
1. flapwise backward whirling
1. longitudinal tower bending
1. lateral tower bending
1. fixed-free drivetrain torsion

600 kW turbine
Demonstration of the HAWCStab tool
Low damped modal shapes – can lead to instabilities

- modal shapes involving lateral tower top movement
- modal shapes involving blade edgewise tip motion
- flutter instability involving 2\textsuperscript{nd} flapwise blade mode and 1\textsuperscript{st} torsional mode
Edgewise blade vibrations

Measured instability

![Graph showing edgewise blade vibration instability](image-url)
Outline

- Introduction to Risø DTU
- The typical wind turbine 2011
- Wind turbine loads and certification
- Aerodynamic and aeroelastic tools
- Aeroelastic stability
- Wind farms and wakes
- Aeroacoustics
- New technology - outlook
- Summary
Wind farms and wakes
Wake operation

The presence of neighboring turbines causes:

1. Reductions in wind speed.
2. Increased turbulence – turbine components fails (especially yaw system).
Power reduction

Models for power prediction exist but nearly all only depend on the upwind turbine thrust coefficient. Large uncertainty present.
Example of increased loads
Load measurements from Vindeby wind farm
Assessment of turbulence intensity
IEC61400-1, Frandsen 2003

For fatigue loads:

\[ I_{\text{eff}} = \frac{\hat{\sigma}_{\text{eff}}}{V_{\text{hub}}} = \frac{1}{V_{\text{hub}}} \left[ (1 - N \ p_w) \hat{\sigma}^m + p_w \sum_{i=1}^{N} \hat{\sigma}_T^m (d_i) \right]^{\frac{1}{m}} ; \ p_w = 0.06 \]

\[ \hat{\sigma}_T = \sqrt{\frac{0.9 V_{\text{hub}}^2}{(1.5 + 0.3 d_i \sqrt{V_{\text{hub}} / c})^2}} + \hat{\sigma}^2 \]

\[ \sigma_1 \geq I_{\text{eff}} \cdot V_{\text{hub}} + 1.28 \hat{\sigma}_\sigma \]

For extreme loads:

\[ I_{\text{eff}} = \frac{1}{V_{\text{hub}}} \max \{ \hat{\sigma}_T \} \]
Computation of half wake with EllipSys3D
Actuator line CFD simulation
Influence of Ambient Turbulence

- Upstream wake asymmetric due to inflow shear
- Ambient turbulence causes rapid vortex breakdown
- Fully turbulent wake more symmetric
- Rapid transition towards bell shaped deficit behind downstream turbine

no ambient turbulence

ambient turbulence
Measured influence of wake meandering

2002-2003 First version of model developed to investigate yaw loads in a wind farm

Illustration of loads from meandering of wake velocity deficit

Local Inflow Angle

Yaw Moment
Different models for increased loading

Effective turbulence model

Wind turbine wake

All wake parameters

effective turbulence

aeroelastic simulations

Dynamic wake meandering (DWM) model

Wind turbine wake

velocity deficit

wake meandering

wake added turbulence

aeroelastic simulations
Load measurements on a NM80 2MW turbine in 3.3D wake

Figure 5. Measured and simulated loads at 8 m s⁻¹ (full lines and crosses) and 10 m s⁻¹ (broken lines and squares)
Outline

- Introduction to Risø DTU
- The typical wind turbine 2011
- Wind turbine loads and certification
- Aerodynamic and aeroelastic tools
- Aeroelastic stability
- Wind farms and wakes

**Aeroacoustics**

- New technology - outlook
- Summary
Aeroacoustics

- broadband noise can often cause problems when siting turbines on land
- trailing edge noise and noise from inflow turbulence are the dominant sources
- max. blade tip speed ratio typically limited to 70 m/s due to noise constraints
- turbines have special low noise control modes by pitching more positive – however, production is reduced
- airfoils, blades and control are designed taking noise into account
- for turbines with a downwind rotor, low frequency noise can be a major problem
Aerodynamic Noise

Wind Turbine Blade:

- leading edge separation possible
- turbulence in oncoming flow
- surface boundary layer
- tip vortex
- trailing edge flow
- transition laminar/turbulent
- wake

$U$
Trailing Edge Noise

\[ u_1, u_2, u_3 \]

\[ U_1(y_2) \]

\[ P(k, \omega) \]

Far field sound

\[ S_P(\omega) \]
TNO Trailing Edge Noise Model

Parchen (1998) combines a diffraction problem solution with knowledge of the turbulent fluctuations in the boundary layer

- **Airfoil Surface Pressure Spectrum** (Blake, 1986)
  Lighthill analogy in spectral domain
  Solution for the Mean shear-Turbulence interaction:

\[
P(k, \omega) = 4 \rho_0^2 \frac{k_1^2}{k_1^2 + k_3^2} \int_0^{+\infty} L_2(y_2) \left( \frac{\partial U_1}{\partial y_2} \right) u_2^2 \cdot \Phi_{22}(k, \omega) \cdot \Phi_m \left[ \omega - U_c k_1 \right] \cdot e^{-ky_2} dy_2
\]

- **Far Field Noise** (Ffowcs Williams and Hall, 1970; Chandiramani, 1974; Chase, 1975; Howe, 1978; Brooks and Hodgson, 1981)

\[
S_P(\omega) = \frac{L_{span}}{4\pi R^2} \int_{-\infty}^{+\infty} \frac{\omega}{c_0 k_1} \cdot P(k_1, \omega) dk_1
\]
Turbulent Inflow Noise Model

Amiet’s Theory (1976)
Linearized Inviscid Theory for flat plate with 0-mean loading

- Inflow turbulence as a harmonic turbulent gust

\[ u_{2,\text{gust}} = v_0 \cdot e^{i(k_1(x_1 - Ut) + k_3x_3)} \]

- Surface pressure response using Sears’ theory:

\[ \Delta P(x_1, x_3, t, k_1, k_3) = 2\pi\rho_0 v_0 g(x_1, k_1, k_3) \cdot e^{i(k_1Ut - k_3x_3)} \]

where \( g \) is the transfer response function
TE and TI Noise Characterization

USING flush-mounted high-frequency MICROPHONES

- **Trailing Edge Noise**
  
  *Surface pressure spectrum near TE is correlated to TE far-field noise*

- **Inflow Turbulence & Related Noise**
  
  *Surface pressure near LE characterizes the inflow turbulence*

- **BL Transition**
  
  *Surface pressure can be used to detect transition (Sudden increase of spectral intensity)*
Airfoils: Tests in wind tunnel

Inlet

Airfoil

Wake rake: Measurement of drag using traversing

LM’s wind tunnel: Test section
Surf. Pres. measurements near TE measured in a wind tunnel

\[ \alpha = 0.0 \text{ [deg]} \]
\[ \alpha = 0.4 \text{ [deg]} \]
\[ \alpha = 0.8 \text{ [deg]} \]
\[ \alpha = 1.2 \text{ [deg]} \]
Measurements on an 80 m diameter rotor – DANAERO project

Comparison Exp./Model

Surface Pressure near TE

![Graph showing surface pressure PSD vs frequency](image)

- CFD/TNO - AoA=7° - V=66.0m/s
- AoA=8° - V=63.5m/s
- AoA=9° - V=61.0m/s
- NM80 Exp. - AoA bin no.1
- AoA bin no.3
- AoA bin no.5
Summary on noise modelling

➢ the models can now be used in a design optimization loop to design low noise airfoils
Outline

- Introduction to Risø DTU
- The typical wind turbine 2011
- Wind turbine loads and certification
- Aerodynamic and aeroelastic tools
- Aeroelastic stability
- Wind farms and wakes
- Aeroacoustics
- New technology - outlook
- Summary
Floating turbines

The HYWIND concept

HYWIND concept by StatoilHydro

- 2.5MW pitch controlled wind turbine
- Floating spar buoy attached to three mooring lines
- Intended for water depths between 120 - 700m
- Demonstration project with Siemens 2.3MW 10km outside west coast of Norway
Combined wave and wind -- Poseidon

- Wave energy platform
- Dimensions are very large. Three turbines can produce extra power from wind – and contribute to the total damping of motion.
Poseidon

Illustration of the three 11 kW GAIA turbines mounted on the demonstration platform. The turbines are two-bladed fixed speed down-wind turbines with free yaw and a teeter mechanism.
DEEPWIND – EU funded project on new floating wind turbine concept
TRAILING EDGE FLAPS

Sensors and DTEG positions

Inflow by pitot tube sensors, $a_{i,j}$ $V_{i,j}$

Rotor speed, $\omega$

Blade pitch angle, $\theta_j$

Blade root bending moment, $M_j$

Table of DTEF

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.7m</td>
</tr>
<tr>
<td>2</td>
<td>5.3m</td>
</tr>
<tr>
<td>3</td>
<td>8.5m</td>
</tr>
<tr>
<td>4</td>
<td>6.5m</td>
</tr>
<tr>
<td>5</td>
<td>3.7m</td>
</tr>
</tbody>
</table>
Outline

- Introduction to Risø DTU
- The typical wind turbine 2011
- Wind turbine loads and certification
- Aerodynamic and aeroelastic tools
- Aeroelastic stability
- Wind farms and wakes
- Aeroacoustics
- New technology - outlook

Summary
Summary of key aeroelastic research issues 2011

- Modeling detailed influence of atmospheric inflow, turbulence and wind shear
- Wake modeling – decreased power – increased loading
- Vibrations at standstill
- Non-linear structural modelling of blades
- Dynamic effects in deep stall
- Structural damping enhancement
- Load alleviation using trailing-edge flaps or other devices
- Modeling floating design concepts
THANK YOU for your attention