Effects of Inflow Wind Condition and Structural Oscillation on Blade Loads of HAWT Rotor

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  - results & discussions
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Many turbines installed in mountainous area, in Japan:
- High turbulence intensity over the complex terrain.
- Special attention should be paid to effects of inflow condition on fatigue load.

Off-shore wind farm (Middelgrunden, DK)

Wind farm in complex terrain area (Tappi, Aomori, JP)

Average wind speed $\bar{U}$ [m/s] measured at 50 m elevation

90% quantile
- 10min average data
- IEC $\overline{TI}$ model

Turbulence intensity $\overline{TI}$ [-]

Average wind speed $\bar{U}$ [m/s] measured at 40 m elevation
Increasing size of wind turbines:

- Decrease in eigen freq. of blade oscillation
  - close to rotational freq. for large rotors
  - possible resonant oscillation of blade

- Increase in non-uniformity of inflow into rotor plane, leads to increased effects from inflow condition

In order to design large wind turbines:

Effects of inflow condition and blade oscillation on the blade loads have to be predicted in design process.
Objective I: Clarify effects of inflow condition on blade loads by simple numerical analysis.

- Yaw misalignment
- Sheared inflow
- Turbulent inflow
- Combined inflow

Objective II: Clarify effects of blade oscillation on blade loads by fluid-oscillation coupled analysis.

- Aerodynamic Analysis: Flow Field around Rotor (Panel Method)
- Oscillation Analysis: Blade Oscillation (Multi-Body Dynamics)

Two-way coupled analysis model
Objective I and Procedure I

Objective I: Clarify effects of inflow condition on blade loads by simple numerical analysis

Procedure I:

1. Wind simulation:
   - Wind shear: Power law
   - Turbulence: Mann model

2. Aerodynamic load calculation:
   - Acceleration Potential Method
Simulation of turbulence by Mann Model

- Generates turbulent wind time series at multiple points on rotor plane
- Takes account of spatial correlation between time series
- Power Spectrum: von Karman Spectrum (isotropic turbulence)

\[ E(k) = \alpha_k \varepsilon^{2/3} L^{5/3} \frac{L^4 k^4}{(1 + L^2 k^2)^{17/6}} \]

- \( L \): turbulent length scale
- \( \alpha_k \): Kolmogorov constant
- \( \varepsilon \): viscous dissipation rate

Example of turbulent inflow by Mann model

- Power Spectral Density of Wind Speed \( E(k) [m^2/s] \)
- Wave Number \( k [m^{-1}] \)
- Wind Speed \( W [m/s] \) over time \( t [s] \) at different heights

Graphs showing the simulation results at different locations (Top, Hub, Bottom) for turbulence.
## Acceleration Potential Method

- Assume **inviscid and incompressible flow**
- Laplace equation for pressure perturbation
  
  \[
  \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = - \frac{1}{\rho} \nabla p
  \]

  **Euler eq.**

  \[
  \nabla^2 p = \frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} = 0
  \]

  **Laplace eq.**

- Representation of rotor blades by spanwise and chordwise pressure distributions
- **Ability to handle** three dimensional unsteady flow 
  **without using empirical constants** unlike BEM

![Diagram showing air particle trajectory and collocation points on rotor blade](image)
Rotor configuration I:

- **Tjæreborg Turbine** (Denmark)

<table>
<thead>
<tr>
<th>number of blades</th>
<th>3</th>
<th>rotor diameter</th>
<th>61 [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>rotational speed</td>
<td>22 [rpm]</td>
<td>rated power output</td>
<td>2 [MW]</td>
</tr>
</tbody>
</table>

Validity of calculation method

Power Coefficient: 

\[ C_P = \frac{P}{\rho W_{hub}^3 \pi R^2 / 2} \]

Tip Speed Ratio: 

\[ \lambda = \frac{\Omega R}{W_{hub}} \]

Ratio of the rotor tip speed to the wind speed

Rotor performance
Examples of inflow conditions

- Yawed inflow (uniform inflow with yaw misalignment)
- Turbulent inflow
- Yawed turbulent inflow (turbulent inflow with yaw misalignment)

Is summation of individual inflow effects on fatigue load equal to combined inflow effects??

Yawed inflow effects are not considered in the fatigue load analysis in IEC standard.
Relative flow to the rotating blade section changes periodically

In the rotor plane ....

- **Upper half**: smaller attack angle → lower blade load
- **Lower half**: larger attack angle → higher blade load

Relative flow to blade section at the top of rotor plane
Relative flow to the rotating blade section changes periodically.

In the rotor plane.....

- **Upper half:**
  - smaller attack angle $\rightarrow$ lower blade load

- **Lower half:**
  - larger attack angle $\rightarrow$ higher blade load

Relative flow to blade section at the bottom of rotor plane.
Relative flow to the rotating blade section changes periodically

In the rotor plane ......

- **Upper half**: smaller attack angle → lower load
- **Lower half**: larger attack angle → higher load

Definition of Flapwise Moment

Flapwise moment fluctuation due to yaw misalignment at \( \lambda = 8 \)
Turbulent Inflow

Turbulent Inflow without Yaw Misalignment

- Blade load due to turbulence
  - Complex fluctuation of blade load
  - Amplitude of fluctuation increases with turbulence intensity $TI$

Turbulence Intensity: $TI = \frac{\sigma}{W_{hub}}$

$\sigma$: standard deviation of velocity fluctuation
$W_{hub}$: velocity at hub height

Flapwise moment fluctuation for various turbulence at $\lambda=8$
### Turbulent Inflow with Yaw Misalignment

#### Fatigue load on blade

- **Yawed uniform inflow condition**
  → Linear increase with yaw misalignment angle
- **Yawed turbulent inflow condition**
  → Non-linear increase with yaw misalignment angle

Blade load fluctuation due to yawed inflow with and without turbulence

Effect of yawed turbulence on fatigue load on blade
Turbulent Inflow with Yaw Misalignment

- Compare effects of turbulent components
  - longitudinal component
  - lateral component
  - vertical component
  - 3d isotropic turbulence

Normal Inflow ($\theta_{yaw}=0$deg)
- longitudinal comp. has dominant effect on Fatigue Load
- small effect from lateral and vertical comp.

Yawed Inflow
- lateral comp. gives larger effects with yaw misalignment angle

Effect of turbulence component and yaw misalignment on fatigue load on blade
Objective I: Clarify the effects of inflow condition on blade loads by simple analysis.

- Yaw misalignment
- Sheared inflow
- Turbulent inflow
- Combined inflow

Objective II: Clarify the effects of blade oscillation on blade loads by fluid-oscillation coupled analysis.

- Aerodynamic Analysis: Flow Field around Rotor (Panel Method)
- Aerodynamic Load
- Oscillation Analysis: Blade Oscillation (Multi-Body Dynamics)
- Displacement & Velocity of Blade Oscillation
- Two-way coupled analysis model
Reference Data: Wind tunnel experiment conducted by NREL (National Renewable Energy Laboratory)

### Configuration of NREL Rotor

<table>
<thead>
<tr>
<th>Blade num.</th>
<th>2</th>
<th>Rotational speed</th>
<th>72 [rpm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor diameter</td>
<td>10 [m]</td>
<td>Wing section</td>
<td>NREL S809</td>
</tr>
</tbody>
</table>

### Calculation Condition

<table>
<thead>
<tr>
<th>Uniform inflow</th>
<th>without turbulence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaw Misalignment</td>
<td>0~30 [deg]</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>5~12 [m/s]</td>
</tr>
</tbody>
</table>
Objective I: Clarify the effects of inflow condition on blade loads by simple analysis

Procedure II: Clarify the effects of blade oscillation on blade loads by fluid-oscillation coupled analysis analysis

Aerodynamic Analysis
Flow Field around Rotor (Panel Method)

Aerodynamic Load
Displacement & Velocity of Blade Oscillation

Oscillation Analysis
Blade Oscillation (Multi-Body Dynamics)

blades, wake vortices and tower are modeled by vortex lattices

Two-way coupled analysis model
### Multi Body Dynamics Model

- Represent rotor blade by combination of **Rigid Bodies** and **Hinge Springs**
- Consider forces on bodies **Aerodynamic, Gravity, Centrifugal, and Coriolis forces** as well as **Restoring and Damping Moments** from Hinges
- Examine **Flapwise** and **Edgewise** oscillations in the present study

### Verification of Oscillation Model

- Compare Eigen Frequencies of Static Blade

<table>
<thead>
<tr>
<th>Mode</th>
<th>Calculation</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flapwise 1st</strong></td>
<td>7.39 Hz</td>
<td>7.31 Hz</td>
</tr>
<tr>
<td>2nd</td>
<td>30.2 Hz</td>
<td>30.1 Hz</td>
</tr>
<tr>
<td><strong>Edgewise 1st</strong></td>
<td>9.27 Hz</td>
<td>9.06 Hz</td>
</tr>
<tr>
<td>2nd</td>
<td>64.9 Hz</td>
<td>-</td>
</tr>
</tbody>
</table>
Coupled Analysis Results

- **Blade Load Fluctuation in Flapwise direction**

  - **Aerodynamic Moment**
    Integrated moment due to aerodynamic force
    
    *Exp. results are obtained from pressure distribution on blade.*

  - **Structural Bending Moment**
    Product of spring constant & bent angle of hinge spring at blade root
    
    *Exp. results are obtained by strain gauge installed at blade root.*

  \[ W=7\text{m/s} \]
  \[ \phi_y=30\text{deg} \]

  Rotation freq.  \( f_{\text{rev}} = 1.14\text{Hz} \)
  1st eigen freq.  \( f_1 = 7.44\text{Hz} \)

  \[ f_{\text{rev}} \]
  \[ 2f_{\text{rev}} \]
  \[ 3f_{\text{rev}} \]
  \[ f_1 \]
Coupled Analysis Results

- **Blade Load Fluctuation in Flapwise direction**
  - **Aerodynamic Moment**
    Peaks at rotation freq. and its harmonics → *due to Rotational Sampling Effects*
  - **Structural Bending Moment**
    Additional peak at 1st eigen freq. of blade structure
  - **From comparison between Exp. and Cal.**
    Calculation results are improved by including tower model.

**Aerodynamic Moment**

<table>
<thead>
<tr>
<th>Frequency $f$ [Hz]</th>
<th>Exp.</th>
<th>Cal.</th>
<th>Cal.+Tower</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{rev}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2f_{rev}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$3f_{rev}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_1$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Structural Bending Moment**

Rotation freq. $f_{rev}=1.14\text{Hz}$
1st eigen freq. $f_1=7.44\text{Hz}$

- \( W=7\text{m/s} \)
- \( \phi_y=30\text{deg} \)
Blade Load Fluctuation in **Edgewise direction**

- **Aerodynamic Moment**
  Amplitude is much smaller than Structural Bending Moment

- **Structural Bending Moment**
  Gravitational Force Effects are dominant

- **Tower Effects on edgewise moment**
  Scarcely seen in calculated results

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**Coupled Analysis Results**

**Aerodynamic Moment**

- Amplitude is much smaller than Structural Bending Moment

**Structural Bending Moment**

- Gravitational Force Effects are dominant

**Tower Effects on edgewise moment**

- Scarcely seen in calculated results

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**Frequency**

- **Wind Speed:** $W=7 \text{m/s}$
- **Yaw Angle:** $\phi_y=30^\circ$
Inflow condition effects such as
- yaw misalignment
- turbulence
on fatigue load of HAWT rotor have been examined by simple numerical calculation.

For turbulent inflow condition,
- Longitudinal component of turbulence has dominant effects on fatigue load.
- Effects from lateral and vertical components are negligible for fatigue load evaluation.

For combined inflow condition of yaw misalignment and turbulence,
- Lateral and vertical components effects increase with yaw misalignment angle.
- 3d turbulence is necessary for fatigue load calculation.
A fluid-oscillation coupled analysis model has been constructed for the estimation of the flapwise and the edgewise blade loads of HAWT rotor.

- Validity of the coupled analysis model is improved by introducing the tower model into the aerodynamic calculation for flapwise component.

- Tower effects can scarcely be seen in the edgewise structural moment, which is dominated by the gravitational force.
Our Future Work I

- **Design of Turbine Control**
  - Include power-train model
  - Decrease fatigue load, power fluctuation
  - Suppress structural oscillation

![Diagram of wind turbine models and coupled analysis]

- Inflow Wind Model
- Aerodynamic Load Calculation Model
- Power-Train Model
- Structural Oscillation Model
- Coupled Analysis
Application to Off-shore Turbine

- Include floating structure model

- Inflow Wind Model
- Aerodynamic Load Calculation Model
- Structural Oscillation Model
- Floating Structure Model

Coupled Analysis
Thank you for your kind attention . . .