Fatigue loadings for rotating shaft of floating offshore wind turbine based on decoupled analysis

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1. Background
2. Objective
3. Analysis method
4. Model
5. Result
6. Conclusion
Offshore wind turbine is one of the fastest growing industries in many areas.
Onshore wind turbine

FOWT

Compared to onshore wind turbine, Loads on FOWT are complex.

Fatigue Damage on the structure

Aerodynamic loads

Hydrodynamic loads

Additional loads due to the motion
For securing the reliability, it is needed to calculate the fatigue damage on structural details of FOWT.

**Loads on rotating shaft**

- **Gravity of rotor**

  \[ F_z = M_g \]
  \[ M_x = M_g l \]
  Due to gravity of rotor

  Stress at red point...
  \[ \sigma = \text{Bending Moment} \times \text{distance from neutral axis}/I \]
  \[ = M_g l \times r \cos(\Omega t)/I \]
  Distance from neutral axis include cosine function

• Repeated stress is serious matter in term of fatigue damage on structure
• Comprehending various loads on rotating shaft, especially, additional loads due to floating structural motion.

• Evaluating the stress response of rotating shaft both of onshore wind turbine and FOWT.

• Comparing these value and examining about impact on fatigue damage.

By using FEM model and numerical analysis
Analysis method for response in wave

**Analysis Step**
- **Preparation**
- **Hydrodynamic Analysis**
- **Motion Analysis**
- **Structural Analysis**

**Output**
- Model (geometry, meshing, stiffness distribution)
- Hydrodynamic pressure distribution
- Displacement, Acceleration distribution
- Stress, Strain, Deformation

**Program used for analysis**
- **SDM**
  - Singularity Distribution Method
- **SSODAC**
  - Shell Stress Oriented Dynamic Analysis Code
- **NASTRAN**
  - NASA Structural Analysis
Analysis method for irregular wave

By using RAO(Response Amplitude Operator) obtained by analysis and wave spectrum, time history of irregular wave can be obtained.

\[ S(\omega) = \frac{0.11T_v}{2\pi} \left( \frac{\omega T_v}{2\pi} \right)^5 H_s^2 \exp \left[ -0.44 \left( \frac{\omega T_v}{2\pi} \right)^4 \right] \]

\[ \text{response}(t) = \sum_{i=0}^{N} \sqrt{2S(\omega_i)}d\omega \text{RAO}(\omega_i) \cos(\omega_i t + \varepsilon_i + \phi_i) \]

Tv: mean wave period
Hs: significant wave height
\( \phi \): phase difference
\( \varepsilon \): random
Analysis method for response in wind

Analysis Step

- Preparation
- Aerodynamic Analysis
- Structural Analysis

Output

- Model (rotated speed)
- Wind condition (speed, steady or turbulence)
- Aerodynamic loads distribution on rotor
- Stress, Strain, Deformation

Program used for analysis

FAST
NASTRAN

Fatigue, Aerodynamic, Structure, Turbulence

By NREL
The National Renewable Energy Laboratory
Analysis method of stress on shaft

Stress of shaft

1. By gravity of rotor \( \sigma = \frac{mgl \times r' \cos(\Omega t)}{I_p} \)

2. By aerodynamic loads on rotor \( \sigma = \frac{M_y \times r' \cos(\Omega t)}{I_p} + \frac{M_z \times r' \sin(\Omega t)}{I_p} \)

3. Additional lift force on blades due to relative velocity by surge & pitch motion

\[
\Delta L = u \frac{dL}{du}, \quad u = \dot{x} + (L + r \cos(\Omega t))\dot{\theta}_y \quad \Rightarrow \quad \Delta M_y = \int^r Lr \cos(\Omega t)dr, \quad \Delta M_z = \int^r Lr \sin(\Omega t)dr
\]

4. Additional bending moment on rotor due to inertia by heave & pitch motion

\( \Delta M_y = -m\ddot{z} - I\ddot{\theta}_y \)
## Configuration of Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Rating</td>
<td>5(MW)</td>
</tr>
<tr>
<td>Rated Rotor Speed</td>
<td>15(rpm)</td>
</tr>
<tr>
<td>Rotor Orientation</td>
<td>Downwind</td>
</tr>
<tr>
<td>Rotor Configuration</td>
<td>3 Blades</td>
</tr>
<tr>
<td>Rotor Mass</td>
<td>110,000(kg)</td>
</tr>
<tr>
<td>Nacelle Mass</td>
<td>240,000(kg)</td>
</tr>
<tr>
<td>Tower Mass</td>
<td>347,460(kg)</td>
</tr>
<tr>
<td>Shaft radius</td>
<td>400(mm)</td>
</tr>
</tbody>
</table>
5MW Wind turbine FEM model

Configuration of FEM Model

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Total Mass</td>
<td>13,854(t)</td>
</tr>
<tr>
<td>Volume</td>
<td>13,517(m³)</td>
</tr>
<tr>
<td>Density</td>
<td>1.025(kg/m³)</td>
</tr>
<tr>
<td>Draft</td>
<td>25.0(m)</td>
</tr>
<tr>
<td>GM</td>
<td>13.41(m)</td>
</tr>
</tbody>
</table>
Environmental condition

**Wave condition**

<table>
<thead>
<tr>
<th>Analysis Condition</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean wave period [Tv]</td>
<td>5.75(s)</td>
</tr>
<tr>
<td>Significant wave height [Hs]</td>
<td>2.5(m)</td>
</tr>
<tr>
<td>Wave heading angle [χ]</td>
<td>180(degree)</td>
</tr>
</tbody>
</table>

**Wind condition**

<table>
<thead>
<tr>
<th>Analysis Condition</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind condition</td>
<td>Turbulent wind</td>
</tr>
<tr>
<td>Intensity</td>
<td>0.2</td>
</tr>
<tr>
<td>Mean wind speed</td>
<td>8(m/s)</td>
</tr>
<tr>
<td>Wind heading angle [χ]</td>
<td>180(degree)</td>
</tr>
</tbody>
</table>
Validity of the model

RAO of Displacement by hydrodynamic loads

In each motion * Good Agreement *
Wind loads on rotor by FAST

\[ F_z = m_{\text{rotor}} g = 1078 \text{(kN)} \]

It is gravity

\[ \chi = 180^\circ \]
Stress on shaft of onshore wind turbine

- Only gravity and aerodynamic loads is considered

Stress range: 80 MPa
Result

Stress on shaft of FOWT

- In addition to gravity and aerodynamic loads, additional loads due to floating body motion are considered.

Almost same

Stress range: 80MPa

Heave & pitch
Conclusion

• Rotating shaft is subjected to various loads. In the case of FOWT, in addition to gravity and aerodynamic loads, additional loads due to floating body motions should be considered.

• The stress by additional loads is around 1-2(MPa). Under the assumed environmental condition, it is not so large.

• The total stress range on shaft is around 80(MPa). In the figure of S-N curve, when the stress range is under black line, the structure has a safety margin. This stress range is well below even when additional loads is considered.

• Additional loads could increase depending on environmental condition. It is needed to study in other condition for securing the reliability.
Thank you for your kind attention!
Appendix
Analysis method

Hydrodynamic pressure

- Singularity distribution method based on linear potential theory

\[ \phi = \phi_0 + \phi_d + \sum_{i=1}^{6} (-j\omega a_i)\phi_i \]

- \( \phi_0 \): incident wave potential
- \( \phi_d \): diffraction potential
- \( \phi_i \): radiation potential in the ith mode (i=1~6)

\(<\text{Boundary condition}>\)

\[
\left( \omega^2 + g \frac{\partial}{\partial z} \right) \phi = 0 \quad \text{at } z=0 \tag{1}
\]

\[
\frac{\partial \phi}{\partial z} = 0 \quad \text{at } z=h \tag{2}
\]

\[
\frac{\partial \phi_d}{\partial n} = -\frac{\partial \phi_0}{\partial n} \quad \text{diffraction} \tag{3}
\]

\[
\frac{\partial \phi_i}{\partial n} = \mathbf{n} \cdot \mathbf{\Omega}_i \quad \text{radiation in the ith mode} \tag{4}
\]

\[ \frac{p}{\rho} = -\frac{\partial \Phi}{\partial t} - g z \]

here, \( \Phi = \text{Re}[\phi e^{-j\omega t}] \)
Analysis method

Equation of motion

\[ m\ddot{x} = f(x, \dot{x}, \ddot{x}, t) \]
Analysis method

Aerodynamic loads

FAST: Fatigue, Aerodynamics, Structures & Turbulence

- FAST code is a comprehensive aero simulator to predict both the extreme and the fatigue loads of horizontal-axis wind turbines (HAWTs) with two- or three-blades.

- It evaluates the aerodynamic loads based on Blade Element momentum theory.

- In the present study, rotor loads at nacelle level will be evaluated using FAST.
Fatigue damage

- Stress histogram is obtained by rainflow counting method.

- Cumulative fatigue damage $D$ is obtained by using Stress histogram and S-N curve.

\[
D = \sum_{i=1}^{s} \left( \frac{n_i}{N_i} \right)
\]

$D$ : Cumulative fatigue damage
$n_i$ : Number of cycles of stress range $\sigma_i$
$N_i$ : Fatigue life corresponding to the stress range

S-N curve:

\[
N = \begin{cases} 
C \cdot \Delta \sigma^{-m} & ; \quad \Delta \sigma \geq (10^{-7} \cdot C)^{1/m} \\
C' \cdot \Delta \sigma'^{-m'} & ; \quad \Delta \sigma \geq (10^{-7} \cdot C')^{1/m'}
\end{cases}
\]
Pressure and Stress distribution by hydrodynamic loads

Pressure distribution by motion analysis
Pressure and inertia distributions are applied to structure

Von Mises Stress distribution by structural analysis
Result

Velocity of surge

Velocity of pitch

Acceleration of heave

Acceleration of pitch
周波数スペクトルは「有義波」で表せる

通常、波浪の周波数スペクトルは1つ山で滑らかな裾を引いている。

周波数スペクトルの標準形

プレットシュナイダー・光易型: \( S(f) = 0.257 H_{1/3}^2 T_{1/3}^2 (T_{1/3} f)^{-5} \exp[-1.03(T_{1/3} f)^{-4}] \)

JONSWAP型: \( S(f) = \beta_j H_{1/3}^2 T_p^{-4} f^{-5} \exp[-1.25(T_p f)^{-4}] \gamma \exp[-(T_p f - 1)^2 / 2\sigma^2] \)

\( \gamma = 1 \sim 7, \ \beta_j: \gamma \)の関数, \( T_p = 1/f_p, \ \sigma: \)定数
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rating</td>
<td>5 MW</td>
</tr>
<tr>
<td>Rotor Orientation, Configuration</td>
<td>Upwind, 3 Blades</td>
</tr>
<tr>
<td>Control</td>
<td>Variable Speed, Collective Pitch</td>
</tr>
<tr>
<td>Drivetrain</td>
<td>High Speed, Multiple-Stage Gearbox</td>
</tr>
<tr>
<td>Rotor, Hub Diameter</td>
<td>126 m, 3 m</td>
</tr>
<tr>
<td>Hub Height</td>
<td>90 m</td>
</tr>
<tr>
<td>Cut-In, Rated, Cut-Out Wind Speed</td>
<td>3 m/s, 11.4 m/s, 25 m/s</td>
</tr>
<tr>
<td>Cut-In, Rated Rotor Speed</td>
<td>6.9 rpm, 12.1 rpm</td>
</tr>
<tr>
<td>Rated Tip Speed</td>
<td>80 m/s</td>
</tr>
<tr>
<td>Overhang, Shaft Tilt, Precone</td>
<td>5 m, 5°, 2.5°</td>
</tr>
<tr>
<td>Rotor Mass</td>
<td>110,000 kg</td>
</tr>
<tr>
<td>Nacelle Mass</td>
<td>240,000 kg</td>
</tr>
<tr>
<td>Tower Mass</td>
<td>347,460 kg</td>
</tr>
<tr>
<td>Coordinate Location of Overall CM</td>
<td>(-0.2 m, 0.0 m, 64.0 m)</td>
</tr>
</tbody>
</table>