Investigating Optimal Leg Distance, using Conceptual Design Optimization

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This talk presents conceptual design optimization of jacket structures for offshore wind turbines.

Design considerations

Design trends

Optimal design problem

minimize $f(x)$

subject to $K(x)u - \Delta P = 0$

$\sigma \leq \sigma(x) \leq \bar{\sigma}$

$\omega \leq \omega(x) \leq \bar{\omega}$
A good jacket design has low mass to minimize material, transportation, and installation costs.
To avoid resonance, the natural frequency must lie in the soft-stiff range between the 1p and 3p rotor frequencies.
Reference jackets in the literature have very different leg distances

OC4 jacket
Designed for NREL 5 MW

INNWIND.EU jacket
Designed for DTU 10 MW
Placing the same tower and turbine on two jackets allows us to compare them.

OC4 jacket
Designed for NREL 5 MW
8 m

JADOP models with DTU 10 MW tower & turbine

INNWIND.EU jacket
Designed for DTU 10 MW
14 m
34 m
When cross sections are equal, a slender jacket will have a lower mass and a lower frequency than a bulky jacket.

JADOP models with DTU
10 MW tower & turbine
Diameters = 1 m
Thicknesses = 50 mm

Slender
1060 tons
0.20 Hz

Bulky
1510 tons
0.27 Hz
To satisfy the fatigue and ultimate limit states, the cross sections have to change when the slenderness change

JADOP models with DTU
10 MW tower & turbine
Diameters = 1 m
Thicknesses = 50 mm

Slender
1060 tons
0.20 Hz

Bulky
1510 tons
0.27 Hz
The optimization problem for conceptual design is formulated with static loads, and constraints on stress, buckling, and frequency.

\[
\begin{align*}
\text{minimize} & \quad f(x) \\
\text{subject to} & \quad K(x)u - f(x) = 0 \\
& \quad \sigma \leq \sigma(x) \leq \bar{\sigma} \\
& \quad \omega \leq \omega(x) \leq \bar{\omega}
\end{align*}
\]

\(x = \text{cross sections}\)

Jacket mass

Stress

Frequency
Damage equivalent loads are used to make an approximate fatigue constraint using static stress constraints:

\[ D = \sum_i n_i (\Delta \sigma_i)^m \frac{\dddot{a}}{\dddot{a}} \leq D_{max} \]
Damage equivalent loads are used to make an approximate fatigue constraint using static stress constraints.

Rainflow counting: $\Delta P_i, n_i$

$$n_T (\Delta P^{1Hz})^m = \sum_i n_i (\Delta P_i)^m$$

$$\Rightarrow \Delta P^{1Hz} = \left( \frac{1}{n_T} \sum_i n_i (\Delta P_i)^m \right)^{1/m}$$

Rainflow counting: $\Delta \sigma, n_i$

$$D = \sum_i \frac{n_i (\Delta \sigma_i)^m}{\bar{a}} \leq D_{max}$$

Equal fatigue damage

Quasi-static behaviour

1 degree of freedom load

High-cycle SN-curve

$$D = \frac{n_T (\Delta \sigma^{1Hz})^m}{\bar{a}} \leq D_{max}$$

$$\Delta \sigma^{1Hz} \leq \overline{\Delta \sigma} = \left( \frac{D_{max} \bar{a}}{T_{life}} \right)^{1/m}$$
The problem is solved using the JAcket Design OPtimization tool JADOP and the open source optimization solver IPOPT

- Parametric input
- Analytic sensitivities
- Many types of constraints

```
% Specify settings
S = settings;

% Specify DTU 10 MW turbine and INNWIND.EU jacket without piles
S.Geometry.Piles = 0;  % 1 for piles, 0 for clamped.
S.Geometry.LegdistB = 24;  % Leg distance at seabed
S.Geometry.LegdistT = 14;  % Leg distance at transition piece
S.Geometry.Sections = 4;  % Number of sections
S.Geometry.Height = 67;  % Jacket height (bottom of transition piece)
S.Geometry.MSL_h = 50;  % Mean sea level
S.Geometry.Turbine = 1;  % 1-DTU10MW, 2-NREL5MW

% Optimization settings
S.Optimization.flag = 1;
S.Optimization.sand_flag = 0;
S.Optimization.maxIter = 500;
S.Optimization.constraints = {'SCF-validity';'Stress ULS';'Buckling';
                             'Equivalent fatigue';'Frequency'};
S.Optimization.variable_linking = '4nv';
S.Optimization.scale_obj = 1;
S.Optimization.con_lim.disp = 10;
S.Optimization.scale_stress = 1e-6;
S.Optimization.con_lim.stress = 350e6;
S.Optimization.con_lim.FLSstress = 11.5e6;
```
With leg distances from the INNWIND.EU jacket, the mass was minimized to 870 tons in 2 minutes on a laptop.

Top leg distance = 14 m
Bottom leg distance = 34 m
Jacket mass = 870 tons
Natural frequency = 0.264 Hz
Computation time = 118 s
Optimization of 400 jackets indicate that an increased top leg distance reduces the jacket mass with about 20 percent.

INNWIND.EU leg distances

Top leg distance = 14 m
Bottom leg distance = 34 m
Since transition piece mass increases with larger top leg distance, the overall mass reduction is much less.
High leg distances at both bottom and top increase the natural frequency

Upper bound on soft-stiff range
Reducing the bottom leg distance of the INNWIND.EU jacket from 34 to 24 meters, reduces both overall mass and frequency
In conclusion, the conceptual design optimization is a fast and useful tool for investigating key parameters such as leg distance.

- Bottom leg distance: 34 m $\Rightarrow$ 24 m
- Mass: -6.7 percent
- Frequency: -2.8 percent

Can also be used for pile stick-up, number of sections, height, etc.
In conclusion, the conceptual design optimization is a fast and useful tool for investigating key parameters such as leg distance.

- Bottom leg distance: 34 m → 24 m
- Mass: -6.7 percent
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Can also be used for pile stick-up, number of sections, height, etc.

Questions?
Design according to DNVGL offshore standard and recommended practices

DNVGL-OS-C101 Design of offshore steel structures

DNVGL-RP-C203 Fatigue design of offshore steel structures

DNV-RP-C202 Buckling strength of shells
Optimal design problem

\[
\begin{align*}
\text{minimize} & \quad f(v) = \rho \sum_{e=1}^{n} A_e (d_e, t_e) l_e \\
\text{subject to} & \quad A v \leq b \\
& \quad K(v) u^l - f^l(v) = 0, \quad \text{for } l = 1, \ldots, n_l \\
& \quad \sigma \leq \sigma_{ch}^{scf}(v, u^l, \gamma_h) \leq \overline{\sigma}, \quad \text{for } e = 1, \ldots, n, h = 1, \ldots, n_h, l = 1, \ldots, n_{FLS} \\
& \quad \sigma^b(v) - \sigma_{ch}(v, u^l, \gamma_h) \leq 0, \quad \text{for } e = 1, \ldots, n, h = 1, \ldots, n_h, l = n_{FLS} + 1, \ldots, n_l \\
& \quad \omega_i \leq \omega_i(v) \leq \overline{\omega}_i, \quad \text{for } i = 1, \ldots, n_f \\
& \quad g_e(v) \leq 0, \quad \text{for } e = 1, \ldots, n \\
& \quad v \leq v \leq \overline{v},
\end{align*}
\]
## Load cases

### Table 3: Description of static load cases

<table>
<thead>
<tr>
<th>Load type</th>
<th>Limit state</th>
<th>Rotation [deg]</th>
<th>Tower top load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Thrust</td>
<td>Fatigue</td>
<td>0</td>
<td>( F_x + M_y + \frac{1}{2} M_z ) from ( \Delta p^{1Hz} )</td>
</tr>
<tr>
<td>2 Thrust</td>
<td>Fatigue</td>
<td>45</td>
<td>( F_x + M_y + \frac{1}{2} M_z ) from ( \Delta p^{1Hz} )</td>
</tr>
<tr>
<td>3 Torsion</td>
<td>Fatigue</td>
<td>0</td>
<td>( \frac{1}{2} F_x + \frac{1}{2} M_y + M_z ) from ( \Delta p^{1Hz} )</td>
</tr>
<tr>
<td>4 Torsion</td>
<td>Fatigue</td>
<td>45</td>
<td>( \frac{1}{2} F_x + \frac{1}{2} M_y + M_z ) from ( \Delta p^{1Hz} )</td>
</tr>
<tr>
<td>5 Thrust</td>
<td>Ultimate</td>
<td>0</td>
<td>( F_x^{max} + M_y^{max} ) from ([5])</td>
</tr>
<tr>
<td>6 Thrust</td>
<td>Ultimate</td>
<td>45</td>
<td>( F_x^{max} + M_y^{max} ) from ([5])</td>
</tr>
<tr>
<td>7 Torsion</td>
<td>Ultimate</td>
<td>0</td>
<td>( M_z^{max} ) from ([5])</td>
</tr>
</tbody>
</table>
Shell buckling

\[ \sigma^b(v) - \sigma_{ehl}(v, u^1, \gamma_h) \leq 0, \]  

(31)

where the shell buckling capacity in compression \( \sigma^b(v) \), is defined as

\[ \sigma^b(v) = \frac{-\sigma^y}{\gamma M \sqrt{1 + \left( \frac{\sigma^y}{f_{Em}} \right)^2}}, \]

\[ f_{Em} = C \frac{\pi^2 E}{12(1-\nu^2)} \left( \frac{t_e}{L_e} \right)^2, \]

\[ C = \sqrt{1 + (\rho \xi)^2} \]  

(32)

\[ \rho = \frac{1}{2 \sqrt{1 + \frac{d_e}{600t_e}}}, \]

\[ \xi = 1.404 \frac{L_e^2}{d_e t_e} \sqrt{1-\nu^2}, \]  

(33)
Column buckling need only be assessed for element $e$ if

$$\frac{(kL_e)^2 A_e}{I_e} \geq \frac{2.5E}{\sigma^y}. \quad (34)$$

where $k = 0.7$ is the effective column length. To avoid assessing column buckling, the inverse of equation (34) can be formulated as a non-linear constraint $g_e(v) \leq 0$, where

$$g_e(v) = \sqrt{\frac{3.2\sigma^y}{E}} kL_e - d_e^2 + 2d_et_e - 2t_e^2}. \quad (35)$$
SCF validity constraints

The linear constraints $Ax \leq b$ enforce the SCF validity range [2], which states that for a joint where a brace is welded onto a leg, the dimensions should satisfy the following relations:

$$0.2d_{Leg} - d_{Brace} \leq 0$$  \hspace{1cm} (17)
$$d_{Brace} - d_{Leg} \leq 0$$ \hspace{1cm} (18)
$$0.2t_{Leg} - t_{Brace} \leq 0$$ \hspace{1cm} (19)
$$t_{Brace} - t_{Leg} \leq 0,$$ \hspace{1cm} (20)

and that for all elements, the following should hold

$$16t - d \leq 0$$ \hspace{1cm} (21)
$$d - 64t \leq 0.$$ \hspace{1cm} (22)
In the analysis of the offshore wind turbine structure, we assume that only normal stress $\sigma(v, u, \xi, \eta, \zeta) \in \mathbb{R}$ is significant. The normal stress in element $e$, position $h$, is computed as

$$\sigma_{eh}(v, u^g_e, \gamma_h) = E b(v, \gamma_h) T_e u^g_e,$$  \hspace{1cm} (12)

where $b(v, \gamma_h) \in \mathbb{R}^{1 \times 12}$ is the strain displacement vector for normal stress at position $h$, and $E$ is the materials Youngs modulus.

To account for stress concentrations in welded tubular joints, the recommended practice [2] provides a method using stress concentration factors (SCFs). This method assumes superposition of the normal stress components coming from axial forces (ax), moments in plane (mi) and moments out of plane (mo). We decompose the normal stress $\sigma_{eh}(v, u^g_e, \gamma_h)$ by decomposing the strain displacement vector:

$$b(v, \gamma_h) = b^{ax}(v, \gamma_h) + b^{mi}(v, \gamma_h) + b^{mo}(v, \gamma_h)$$  \hspace{1cm} (13)

The recommended practice then provides coefficients that are to be multiplied onto each stress component. These coefficients are functions of diameter and thickness of all elements in the joint, as well as joint geometry, and the position $h$ along the element circumference. The number of hot spots $n_h$ in each element should be at least eight. The scf-stress $\sigma^{scf}_{eh}(v, u^g_e, \gamma_h)$ in element $e$, hot spot $h$ is computed as

$$\sigma^{scf}_{eh}(v, u^g_e) = b^{scf}_{eh}(v, \gamma_h) T_e u^g_e$$  \hspace{1cm} (14)

$$b^{scf}_{eh}(v, \gamma_h) = SCF^{ax}_{eh}(v) b^{ax}_{eh}(v, \gamma_h) + SCF^{mi}_{eh}(v) b^{mi}_{eh}(v, \gamma_h) + SCF^{mo}_{eh}(v) b^{mo}_{eh}(v, \gamma_h)$$  \hspace{1cm} (15)